CAFRI Training Manual-2025/1

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Training Manual

on

Agroforestry Innovations for Climate-Resilient Development, Transformative Land Use, and Livelihood Security

14 - 23 November, 2025

Editors
Asha Ram
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Hirdayesh Anuragi
Naresh Kumar
Ayyanadar Arunachalam

Sponsored by
U.P. Council of Agricultural Research

ICAR-Central Agroforestry Research Institute
Jhansi 284003, Uttar Pradesh

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Citation:
Ram A., Yadav, A., Anuragi, H., Kumar N., & Arunachalam A. 2025. Agroforestry Innovations for Climate-Resilient Development, Transformative Land Use, and Livelihood Security. ICAR-CAFRI Training Manual 2025/1: 215p. ISBN: 978-81-971641-6-3

Published by:
ICAR-Central Agroforestry Research Institute,
Jhansi 284003, Uttar Pradesh
978-81-971641-6-3

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Printed by
Rudra Enterprises,
Jhansi, Uttar Pradesh.
7007122381

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Foreword

Agroforestry innovations play a pivotal role in strengthening climate-resilient development by integrating trees, crops, and livestock in ways that enhance ecological stability and buffer farming communities against climate variability. Modern advancements have enabled the selection and plantation of climate-smart tree species, improved water-use efficiency, and enhanced carbon sequestration capacities. These systems moderate microclimate, reduce soil degradation, enhance biodiversity, and provide resilience against droughts, floods, and heatwavesmaking agroforestry a cornerstone of sustainable natural resource management to offset the climate change.

Transformative land use under agroforestry is driven by innovative approaches that rehabilitate degraded lands, diversify farm landscapes, and increase system productivity. Integrating precision agroforestry tools, improved planting materials, GIS-based land-use planning, and species distribution modelling has enabled informed decision-making for optimizing tree–crop combinations. Such innovations help in restoring ecological functions, improving soil carbon dynamics, enhancing watershed productivity, and converting underutilized or fragile lands into productive and sustainable treescapes. As a result, agroforestry transforms conventional farming into multifunctional landscapes with long-term environmental and socio-economic benefits.

Agroforestry also significantly contributes to improving livelihood security by providing diversified income from timber, fruits, NTFPs, fodder, and value-added tree-based products. The inclusion of innovative market linkages, community-based enterprises, and climate-resilient value chains further enhance economic opportunities for rural households. Collectively, these innovations make agroforestry a viable pathway for climate-resilient development, sustainable land transformation, and inclusive livelihood enhancement.

The training manual on **"Agroforestry Innovations for Climate-Resilient Development, Transformative Land Use, and Livelihood Security"** is an important document designed to equip researchers, academicians, extension personnel, and practitioners with updated knowledge, tools, and methodologies essential for advancing climate-smart agroforestry. It integrates recent scientific advancements, practical field innovations, and policy perspectives that support sustainable land-use transformation, ecosystem restoration, and diversified livelihood opportunities. By bringing together contributions from subject experts across diverse domains, the manual serves as a comprehensive guide for understanding, planning, and implementing resilient agroforestry systems that address current climate risks while ensuring long-term productivity, environmental sustainability, and socio-economic stability for farming communities.

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PREFACE

The Winter School on *"Agroforestry Innovations for Climate-Resilient Development, Transformative Land Use, and Livelihood Security"* has been conceived to address the growing need for climate-smart approaches that integrate ecological sustainability with improved livelihood outcomes. As climate variability intensifies and pressures on natural resources increase, agroforestry has emerged as a powerful strategy for building resilient landscapes, restoring degraded ecosystems, and enhancing the adaptive capacity of farming communities.

This training manual has been developed to provide a comprehensive resource for researchers, academicians, extension personnel, and field practitioners engaged in the advancement of agroforestry systems and related interventions. It compiles recent scientific insights, emerging innovations, field-tested practices, and policy frameworks that support climate-resilient land use. The contents span multiple dimensions of agroforestry including species selection, climate-smart interventions, precision tools, ecosystem services assessment, carbon dynamics, landscape restoration, and livelihood diversification.

The manual also reflects contributions from experts across various disciplines, whose collective experience enriches its scientific and practical relevance. Each chapter is designed to equip participants with the knowledge, analytical tools, and field perspectives required to plan, implement, and evaluate agroforestry interventions at farm, landscape, and regional scales.

We hope this manual will serve as a valuable reference not only for participants of the Winter School but also for a wider community of stakeholders working toward sustainable agriculture including agroforestry adoption, natural resource management, and climate-resilient rural development. It is our sincere belief that the knowledge shared through this programme will inspire innovative thinking and foster collaborative efforts aimed at strengthening agroforestry-based solutions for future challenges.

We extend our sincere gratitude to the Uttar Pradesh Council of Agricultural Research (UPCAR) for their generous financial support. We also thank all resource persons, contributors, reviewers, and partnering agencies for their valuable inputs in the preparation of this manual. We gratefully acknowledge the continuous guidance and encouragement provided by the institutional leadership in organizing this Winter School.

- Coordinating Team

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Agroforestry- An Overview

Harish Sharma, Naresh Kumar, Asha Ram, Ashok Yadav, Ronak Yadav, Guntukogula Pattabhi Sandeep, Badre Alam, AK Handa & A. Arunachalam
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Introduction

Agroforestry, in scientific terms, represents a multifunctional land-use system that combines the cultivation of trees with agricultural crops within the same land unit. It involves the intentional retention or planting of trees along field boundaries, farm bunds, or within agricultural landscapes to optimize resource utilization and productivity. This practice, deeply rooted in traditional farming systems, has evolved over centuries and diversified across the various agro-climatic zones of India in response to topographic, climatic, edaphic, and biotic factors. India's natural resource base illustrates significant pressure on limited land and water assets, as 18 percent of the global human population and 15 percent of global livestock are sustained by merely 2.4 percent of the world's geographical area, including 1.5 percent forest and pastureland and 4.2 percent freshwater resources. Despite rapid urbanization and economic growth, the agricultural sector faces multifaceted challenges such as population expansion, food and nutritional insecurity, resource degradation, climate variability, declining soil health, shrinking landholdings, stagnating farm incomes, youth disinterest in agriculture, and restrictive global trade policies (ICAR, 2020). Within this context, agroforestry in India embodies a dynamic and context-specific integration of agriculture and forestry that generates ecological, economic, and social benefits tailored to national development goals. The system offers a viable mechanism to mitigate production risks, address shortages of inputs and essential resources such as small timber and fuelwood, and reduce labor dependency, particularly for small and marginal farmers. By interlinking trees, crops, and livestock in synergistic ways, agroforestry contributes to resolving issues related to food and nutritional security, energy sufficiency, rural employment, and environmental sustainability. Moreover, agroforestry practices directly support India's commitments to international and national environmental and developmental frameworks, including the Paris Agreement, the Bonn Challenge, the United Nations Sustainable Development Goals (SDGs), the United Nations Convention to Combat Desertification (UNCCD), the Green India Mission, and the national objective of doubling farmers' income (PIB, 2024). As a holistic system, agroforestry bridges sustainability with profitability, promoting long-term productivity and ecological resilience. The adoption and success of agroforestry technologies are influenced by edaphic and climatic conditions, socioeconomic characteristics of farming households, and management practices shaped by physical, demographic, and institutional factors (Bayard *et al*., 2007).

Historical Background

Roots of the agroforestry can be traced in several traditional Indian farming systems sustaining rural communities such as home gardens, silvipastoral systems and "trees outside forests". The formal recognition came with ICAR's AICRP on Agroforestry in 1983, establishing coordinated research across diverse agro-ecological regions, which has now spread across 37 centers with 26 in SAUs, 10 in ICAR and 01 in ICFRE Institutes. Institutionalization of agroforestry in India happened with the establishment of the National Research Centre for Agroforestry (NRCAF) as a unit of ICAR in Jhansi, Uttar Pradesh on 8th May, 1988 which was renamed as ICAR- Central Agroforestry Research Institute on 1st December, 2014. It is a multidisciplinary premier research institute of the Indian Council of Agricultural Research (ICAR) with a major focus on integrating trees, crops and livestock on the same farmland. The foundation for regulating, promoting and financing agroforestry nationwide was laid with the existence of National Agroforestry Policy, 2014. Greening and Restoration of Wasteland with Agroforestry (GROW) portal launched by NITI Aayog is a multi-institutional effort led by NITI Aayog to assess agroforestry suitability across all districts in India (PIB, 2024).

Agroforestry in India

Agroforestry is a sought-after sustainable land use system due to its contribution to livelihoods, nutrition, energy and environmental security. Agroforestry along with contributing towards the country's tree cover and enhancing ecosystem services; also meets the bulk of the country's demand for wood. Currently, agroforestry covers 8.65% of India's total geographical area, totalling about 28.42 million hectares (Arunachalam et al., 2022). At present, agroforestry meets almost 50 percent of fuelwood needs for the country, around 66 percent of small timber, 70-80 percent of plywood, 60 percent of the raw material for paper pulp and 9-11 percent of the green fodder requirement of livestock, as well as meeting subsistence needs of households for food, fruit, fiber, medicine etc. (Gupta et al., 2021). Agroforestry is undertaken throughout the country in all climatic regions. States like Uttar Pradesh (1.9 million hectares), Maharashtra (1.6 million hectares), and Rajasthan (1.6 million hectares) lead the coverage in terms of area. However, the area under agroforestry relative to the net sown area of the state is highest among Jharkhand (21 percent), Andhra Pradesh and Telangana (19 percent) and Bihar (14 percent). Poplars, *Eucalyptus*, *Dalbergia*, Neem, *Acacia*, *Melia*, *Tectona*, *Ailanthus*, *Gmelina*, Bamboo, *Leucaena*, *Casuarina* and *Mangium* hybrid are some popular trees integrated under agroforestry.

Benefits of agroforestry

Agroforestry is increasingly recognized as a multifunctional land-use strategy that contributes significantly to both climate change mitigation and adaptation (Mosquera-Losada et al., 2018). The carbon sequestration potential of agroforestry systems, however, demonstrates substantial spatial and temporal variability, ranging from 0.29 to 15.21 Mg ha^{-1} yr^{-1}, influenced by factors such as site-specific environmental conditions, stand age, species composition, and management intensity (Nair et al., 2009). The integration of trees within agricultural landscapes provides alternative sources of fuel, fodder, and fiber, thereby reducing dependency on natural forests. This process mitigates deforestation and forest degradation, indirectly contributing to atmospheric carbon stabilization. In addition to carbon storage, agroforestry systems play a vital role in regulating nitrogen (N) dynamics by minimizing losses from soil erosion, surface runoff, leaching, and gaseous emissions of nitrogenous compounds such as nitric oxide (NO) and nitrous oxide (N_2O) (Muchane et al., 2020). These systems promote internal nitrogen cycling through mechanisms such as biological N fixation and organic matter incorporation, consequently reducing reliance on synthetic fertilizers and contributing to greenhouse gas mitigation (Kim and Isaac, 2022). Furthermore, integration of forage-producing tree species can enhance feed quality and digestibility, thereby lowering methane (CH_4) emissions associated with enteric fermentation in ruminants (Thornton and Herrero, 2010; Torres et al., 2017). From an economic standpoint, agroforestry enhances livelihood resilience and farm profitability by diversifying income streams, stabilizing yields, and reducing vulnerability to climatic stressors such as drought, wind, and water-related damage. Ecologically, well-managed agroforestry systems improve microclimatic regulation, soil structure, and fertility, enhance soil moisture retention, control pest populations, facilitate pollination, and create habitats that support biodiversity (Datta et al., 2024). Beyond environmental and agronomic dimensions, agroforestry also contributes to rural socioeconomic development through employment generation, food security improvement, local economic strengthening, and nutritional enhancement (Gonçalves et al., 2021; Smith et al., 2022). Furthermore, inclusive and participatory agroforestry practices have been shown to address gender disparities, a critical consideration in climate adaptation strategies given the disproportionate impacts of climate change on women.

Future perspectives in agroforestry

The Prime Minister's vision for Indian agriculture under the Viksit Bharat 2047 framework emphasizes the transformation of the agricultural sector into a modern, resilient, and globally competitive system while ensuring farmers' welfare and national food security. This vision is anchored in the principle of Atmanirbhar Krishi (self-reliant agriculture), positioned as a cornerstone of a developed India. By 2047, the agricultural landscape is expected to evolve from a predominantly livelihood-based activity into a technologically advanced, export-oriented, and environmentally sustainable enterprise, thereby enhancing farm prosperity and contributing significantly to national self-reliance and economic development. However, India, being the seventh largest country in the world, faces considerable challenges such as urban expansion, land degradation, and resource imbalances. Approximately 16.96% of the country's Total Geographical Area (TGA) is classified as wasteland, necessitating its conversion to productive use. To address this, geospatial technologies and Geographic Information Systems (GIS) are employed for mapping and prioritizing wastelands suitable for agroforestry interventions (PIB, 2024). In alignment with its Nationally Determined Contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC), India has committed to establishing an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent. Agroforestry serves as a key strategy to achieve this target by enhancing tree cover and promoting sustainable land use. It presents a viable approach to simultaneously address environmental, economic, and resource challenges by supporting diversified production while maintaining ecological balance. Promotion of agroforestry is particularly critical for three primary objectives: reducing dependence on imported wood and wood products, enhancing carbon sequestration to mitigate climate change at both national and global levels, and optimizing the use of underutilized arable land. Additionally, fallow and culturable wastelands can be rehabilitated for productive purposes through agroforestry practices. Recognizing the multifaceted benefits of agroforestry, the Union Budget of India for the fiscal year 2022–23 identified the promotion of agroforestry and private forestry as a national priority.

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Role of AICRP on Agroforestry in Treescapes

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Agroforestry as an independent research field in science was established in 1970's. It was an emerging area till the last decade. With IPCC and other international organisations emphasised and highlighted the ecological implication of adopting agroforestry, there has phenomenal increase acceptance of agroforestry as form of landuse practice. There is no denial on the fact that, there is a continued global attention for agroforestry due to its multiple and cross benefits to sectors including livestock and pastoralism, with additional benefits towards resilient agriculture and farming systems.

Perceptions on Agroforestry

It is generally perceived that agroforestry is a combination of agriculture and forestry. More specifically, it is stated as a land use that combines aspects of both, including the agricultural use of trees. The accurate description of agroforestry is – "Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos etc.) are deliberately used on the same land management unit as crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions between the different components". Subsequently, the definition of agroforestry was simplified and modified to highlights its contribution to the environment and natural resource management. fundamentally, the difference was the usage of the word "trees" instead of "wood perennials". This subsequently led to contextualizing agroforestry as a forestry-centric subject but on the contrary, it is more multidisciplinary. Agroforestry per se is more than multidisciplinary.

The FAO classifies agroforestry as one form of Trees outside Forests in its Global Forest Resource Assessment Reports. In Indian scenario, there are two other concepts that has close resemblance to the agroforestry but there are distinct and unique *i.e.,* Farm Forestry and Social Forestry.

- **Farm forestry** – The practice of cultivating and managing trees in the compact block on agricultural lands. The typical man-made plantations are examples of this practice.
- **Social Forestry** - The term 'Social Forestry, for the first time was used by the Forest Scientist Westoby, at the 9th Commonwealth Forestry congress held in 1968 in New Delhi. He defined that, "Social Forestry, is a forestry which aims at producing a

flow of protection and recreational benefits for the Community". The term social forestry is difficult to define precisely but is generally understood to mean tree-growing (including associated products, e.g. bamboo, grasses, legumes) for rural development. There are also opinions that the social forestry concept encompasses farm forestry, community forestry, extension forestry and agroforestry. Yet, the differences between these three terminologies have been listed in Table 1.

Table 1. Difference between farm forestry, social forestry and agroforestry

S.No.	Parameter	Farm Forestry	Social Forestry	Agroforestry
1.	Ownership of the land	Owned by individual	Government lands mostly or community lands	Owned by individuals
2.	Choice of tree species	Partial control is the choice of species is guided by the forest department or programme implementing agency	Full control on the choice of species by the forest department or implementation agency	The individual has full freedom to choose the species based on edaphic climatic conditions.
3.	Remuneration	After a long gestation period to the individual	After a long gestation period to the community	As soon as possible for the individual compared to other forms.

The systematic development of agroforestry research can be traced back to the initiatives of the Canada's International Development Research Centre (IDRC), Canada and FAO, which led to the establishment of International Centre for Research in Agroforestry in 1977 (currently known as World Agroforestry Centre). While there was debate and deliberation on the relevance of agroforestry in temperate countries, India was a pioneer in adopting and promoting agroforestry way back in 1983 itself. Here, the history of agroforestry research and its contribution are narrated briefly for the benefit of readers.

Institutionalisation of agroforestry research in India

The Indian Council of Agricultural Research (ICAR) organised a National Agroforestry Seminar at Imphal in 1979 which led to the formulation of All India Coordinated Research Project on Agroforestry in 1983. Initially, this project was aimed at scientific enquiry and analysis of existing tree-based land-use systems and with subsequent findings from this project a dedicated research institute for agroforestry was created in 1988 – the National Research Centre for Agroforestry (currently known as the ICAR-Central Agroforestry Research Institute). In simple words, the institute is mandate with agroforestry research, extension and training. One of the prominent scientists in agroforestry, Dr. P.K.R. Nair says that the period between 1977 to 1987 as the decade of agroforestry research and concept development and institutionalization at global level. It will be apt to say that during same period agroforestry has been institutionalised here in India also. The ICAR-Central Agroforestry Research Institute also started to coordinate the All India Coordinated Research Project (AICRP) on Agroforestry from 1997 with the following objectives

- Screening and genetic upgrading of selected plant species for their compatibility in different agroforestry systems
- To optimize tree-intercrop combination for different regions
- Performance enhancement of the pre-dominant agroforestry systems being already practiced by the farmers
- To upgrade and refine the existing technologies for higher productivity and sustainability

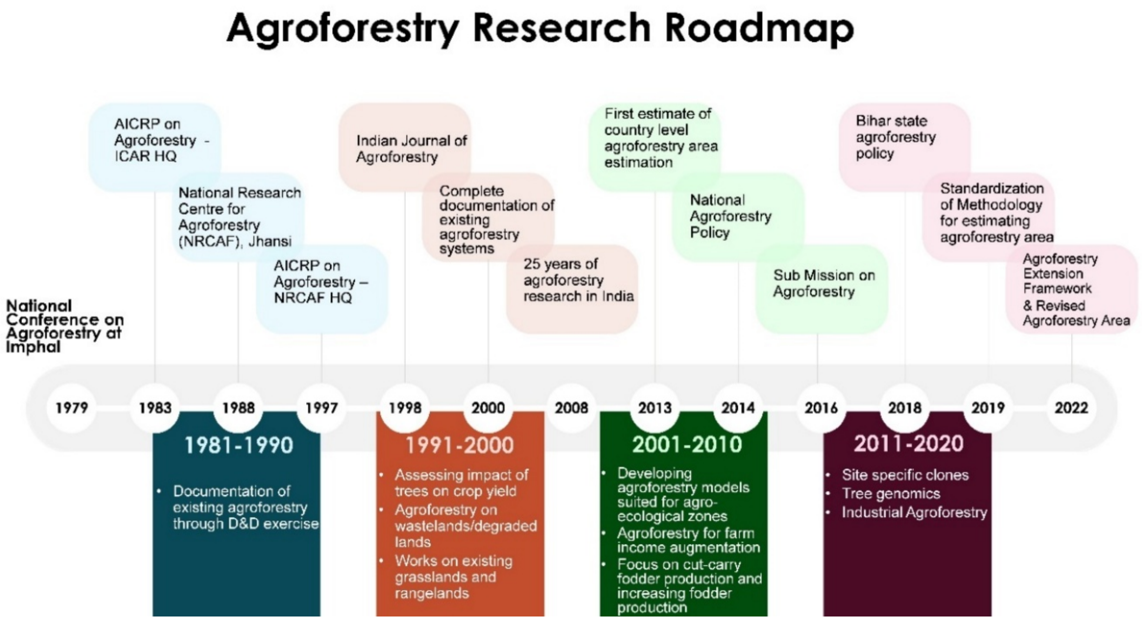

Figure 1. Salient achievements of ICAR-led agroforestry research in the country

As of today, the AICRP on Agroforestry is implemented in 37 centres across different agro-climatic zones of the country and all these centres are working in different aspects of agroforestry. For instance, one of the major works of all these centres was the screening and genetic upgrading of selected plant species for their compatibility in different agroforestry systems. Owing to the systematic efforts, about 184 promising tree species germplasms were collected and are being evaluated for its superiority. In this regard, registration of the elite germplasm has been done like shisham by NRCAF (Bundel-1 and Bundel-2) and GBPUAT, Pantnagar (PS 52), poplar clones (L-48/89, L-47/88) by PAU, Ludhiana, Pant Poplar by GBPUAT, Pantnagar, teak clone (PDKV/AF-1) by College of Agriculture, Nagpur and eucalyptus (SRY-16) by MPKV, Rahuri. Similarly, in neem, elite germplasm with high yield and high, stable azadirachtin content have been identified and are further explored for genetic gains. The AICRP on Agroforestry centres have been also exploring new species to be incorporated into agroforestry systems. With industrial agroforestry and contract farming gaining popularity, fast growing species like *Melia dubia, Anthocephalus cadamba and Melia azedarach* were focused in recent years and promising clones like Malabar Neem (*Melia dubia*) - MTP 1, MTP 2 & MTP 3; Kadam (*Anthocephalus cadamba*) - MTP 2 by TNAU centre; and *Melia azedarach* - Punjab Dek 1 & Punjab Dek 2 by PAU centre was also released. Agroforestry research does not focus on timber yielding trees alone, NTFPs trees were also screened for superior genetic gains and clones/varieties like Undi (*Calophyllum inophyllum*) clone KKVCI-03 by BSKKV centre; Imli (*Tamarindus indica*) varieties viz., DTS-1 and DTS-2 by UAS Dharwad centre; and GKVK-17 Tamarind variety for commercial cultivation to Eastern Dry of Karnataka was also released recently.

As the objective is also to screen plant species for their compatibility in different agroforestry, the AICRP on Agroforestry centres have also screened crop varieties suitable for specific agroforestry systems (models). For instance, Wheat varieties WH 1105, PBW 677, PBW 725, PBW 502, DBW 17, PBW 550 and PBW 621 are suitable for Popular based agroforestry system in Punjab region. The findings from RPCAU centre state that Krishna-258, a Til (*Sesamum indicum*) variety is superior and suitable for intercropping up to 5 years in the Shisham (*Dalbergia sissoo*) based agroforestry system in Bihar.

The continuous effort to the AICRP on Agroforestry in the past 40 years has translated to develop agroforestry system (models) specific different agro-ecologcial reasons of the country. For instance, in Deccan Plateau having 600-1000 mm rainfall can adopt a) Three-tier Agroforestry System for Paddy Growing Area with Teak and Mango as Tree component and Paddy (Kharif); Gram, Black gram, Linseed, Lathyrus (Kharif) as crop component; b) Sapota-Teak based Agroforestry System for Hill Zone of Karnataka with Teak and Sapota as Tree component and Paddy (Kharif); South African Maize, Sun hemp (Kharif) as crop component; and c) Tamarind based Silvi-horticultural System with *Tamarindus indica*, Eucalyptus and Casuarina as Tree component and Natural grass (DTS-1, DTS-2 and SMG-13 as crop component for pasture/fodder. Similarly for specific agroforestry systems for all the 20 agro-ecological zones along with their economic analysis have been developed for the country.

India has always been a pioneer in estimating the area under agroforestry. Earlier attempts at the country level revealed estimates varying from 17.45 to 23.25 million ha and many regional estimates are also reported. There are papers predicting the potential area suitable for agroforestry in India. Despite the predictions, there are no actual estimates to date. ICAR-Central Agroforestry Research Institute (CAFRI), a dedicated research institute for agroforestry in the Asia-Pacific region took up the mapping of agroforestry areas using geospatial technologies. The preliminary work on 13 out of 15 agro-climatic zones reported an area of 23.25 m ha in 2019. Thus, agroforestry as scientific discipline has been evolved in the country and with support of all stakeholders. This article briefly narrated the effort of ICAR led agroforestry research in the country.

Conclusion

The continuous and coherent efforts of the scientists and researchers, including the entire NARS (National Agricultural Research System) in documenting traditional and commercial form of agroforestry, designing science led agroforestry interventions by experimenting different tree+crop+livestock for different agro-climatic conditions through long term and coordinated trials has led to the progress of agroforestry. These efforts were benchmarked agroforestry potential in the country which got global recognition as the India hosted the IIIrd World Agroforestry Congress where the government unveiled the maiden Agroforestry Policy for the country.

Taking essence of the policy, the government rolled out projects and schemes in different states through Sub-Mission on Agroforestry that gave fruitful results. Thus, AICRP on Agroforestry led by the Indian Council of Agricultural Research became the unique project that laid foundations for the Indian agroforestry *per se*.

Soil sampling, biomass estimation, carbon biomass quantification, carbon stock, and accounting tools in agroforestry systems

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Introduction

Agroforestry is a typical agroecosystem in which trees are intentionally integrated with crops, pastures and/or livestocks, and are recognized as possible land use management systems that can sustain or enhance soil organic carbon (SOC) stocks (Debnath et al. 2025). Agroforestry systems enhance soil fertility, regulate microclimate, improve water-use efficiency, and support long-term productivity (Jose 2009). One of the most significant environmental benefits of agroforestry is its ability to capture and store carbon in both vegetation and soils, thereby offset climate change. To measure these benefits in a consistent and scientifically sound manner, practitioners must develop strong skills in soil sampling, biomass measurement, and carbon stock estimation (Montagnini and Nair 2004). These components provide the foundation for understanding how agroforestry interventions influence soil organic carbon levels, tree growth, ecosystem functioning, and overall carbon sequestration potential (Ketterings et al. 2001). With growing demand from governments, investors, and carbon markets for reliable data, the use of standardized carbon accounting tools has become essential. Such tools help translate field measurements into clear, reportable carbon values and support evidence-based planning, monitoring, and evaluation. This chapter introduces field-friendly methods, step-by-step procedures, and practical tools that enable agroforestry professionals to quantify carbon stocks in soils and biomasses accurately and confidently.

Soil sampling

Soil sampling and analysis is a valuable nutrient advantage tool, providing insight into the nutrient and general fertility status of surface (and if analysed, sub-surface) soil layers. Soil analysis is normally undertaken for one of the three reasons. These are: predictive-to check the fertility or nutrient status of soils and for better prediction of nutrient requirements by crop; monitoring-to assess the suitability of current management practices over time, adjusting existing fertilizer programs if necessary to ensure optimum yields are achieved; and 3. diagnostic-to determine the reason for poor growth (troubleshooting), or to check accumulation of mineral elements which is toxic to plants.

Goals of soil sampling

- Obtain samples that accurately represent the field from which they were taken
- Estimate the amount of nutrients that should be applied to provide the greatest economic return to the grower
- Estimate the variation that exists within the field and how the nutrients are distributed spatially
- Monitor the changes in nutrient status of the field over time

Sampling tools

Tools that may be used to take a soil sample include spade/shovel or *khurpi*, screw type auger or tube auger, and soil cores. Sample tube or auger should be either stainless steel or chrome plated. For soft and moist soil sampling tube auger, spade/shovel or *khurpi* is an appropriate tool. The screw type auger is especially useful when sampling heavily compacted or hard and dry soil as well as sampling at greater depths that a tube auger can not penetrate. Using a spade or *khurpi*, a "V" shaped cut may be first made up to the plough layer (vertical depth 15 cm) and about 2 cm uniformly thick slice is taken out from one clean side. In agroforestry, soil cores and soil sampling rigs (motorized) up to 1 m length is usually used for soil sampling. Soil cores/rigs made of GI pipes/stainless steel pipes of suitable length may be hammered into the corresponding depth and the soil core in the tube may be drawn as sample.

Soil sampling strategies

a. When is the best time to collect soil samples?

The time of sampling obviously depends on a number of factors. Soil sampling time in general is discussed below. In case of plants showing any deficiency symptoms such as yellowing of leaves, plant tissue samples should also be collected along with soil samples at the time of sampling.

Fig. Soil sampling rig used for soil collection from agroforestry system

Alley crops

For alley crops, topsoil sampling is required at least one month prior to planting/transplanting to determine basal dose of fertilizers. However, if there is a likely requirement of any amelioration (such as lime or gypsum) sampling is required two to three months prior to planting to ensure that sufficient time be given to the ameliorant to react with soil. Sub-surface sampling is mandatory in situations where salinity or acidity is potential problems.

Tree plantation

Pre-plant: A surface and subsurface soil sampling should be carried out in the field where a new plantation is going to be established, prior to planting. Analysis of surface soil identifies the fertility status of soil, while subsurface soil provides the information regarding potential problems such as salinity/sodicity or acidity/alkalinity in soil and thereby reclamation measures needed to be taken care of (like application of gypsum/lime or leaching of soil profile etc.).

Establishment: Once the plantation is established, surface soil sampling should be done in order to ensure that fertilizer inputs and ameliorants have incorporated in soil. At this stage it is very important to monitor that no nutrient is in deficiency or toxic levels in soil. At this stage, soil sampling is generally required in late winter or early spring.

b. How frequently should soil samples be sampled?

The frequency with which soil samples should be collected depends on the specific soil test and value of the alley crops. It is always recommended that soil sampling and analysis should be done in every 2-3 years in order to monitor soil nutrient status.

c. What will be the depth of sampling?

For alley crops such as field crops, vegetables, flowers, medicinal plants the soil samples should be sampled from 0-15 cm (plough/surface layer). Whereas in case of agroforestry systems, sampling should be carried out at different soil depths *viz*. 0-30, 30-60 and 60-90 cm as the trees are deep rooted in nature; and soil samples should be collected from 4-5 pits dug in about half a hector field. It is helpful to sample to the same depth each time a soil is sampled, so that year to year samples can be directly compared to monitor changes over time.

d. Where to sample?

When considering which production areas to sample there are a number of factors to consider. Ideally, it would be great to sample every production unit or soil type, however time and costs may make this approach unfavorable. In selecting areas for soil sampling consider the following:

- Draw samples separately from the alleys and tree-rows
- Don't mix soil samples from different production systems, or areas which have been farmed separately
- Sample high and low yield areas separately
- Variations in slope, soil type, colour, texture, crop growth or in past treatments should be sampled separately, provided that this area can be treated separately
- Larger areas may divide into appropriate number of smaller homogeneous units for better representation
- When trouble-shooting take soil samples (surface and sub-surface) along with plant tissue from both the good and the poor areas

Area not suitable for soil sampling

- Unusual areas such as stock camps, dam sites, within 10 to 20 m of current and old fence lines, timber burns, compost piles, marshy tracts, areas near wells and the corners of paddocks, which have been cultivated or planted from the perimeter inwards, poorly drained areas etc.
- Areas of poor growth or excessively good growth, like dung and urine patches
- Areas of differing soil type, drainage patterns, fertilizer usage, very wet conditions, stock tracks, windbreaks, fertiliser dump sites
- Areas that have been fertilized or limed should not be sampled until a minimum of 8 weeks has elapsed since application

How to sample?

a. **Zone to Zone:** This design is used for changes in soil types and trends across sampling areas (precision farming). Samples are taken from each zone and analysed separately. This design should be adopted in all sampling strategies.
b. **Zigzag:** If care is taken this provides good coverage of the sampling area, making it the ideal design for diagnostic sampling. The degree and type of bias vary with experience of the sampling personnel. Generally, it is the most commonly used method for soil sampling, and suitable for areas less than 10 ha.
c. **Transect:** Spot samples are taken at regular intervals along a defined transect. This design allows the same or different operators to repeat the sampling with good precision. Transect sampling is the simplest sampling method in agroforestry system as the same sample line can be used each season for monitoring fertility trends.

d. Cluster: This design involves sampling around several points within a sampling area. Where sampling points are defined (GPS or plotted on map), cluster sampling can produce low variability. However, the results are less likely to be representative of the sampled area.

e. Grid: This design is systematic, with individual samples taken at regular intervals across the sampling area and analysed separately. It is used in precision farming and can help overcome landscape or yield variation, particularly if there is a trend across the sampling area. This design can be expensive if many sampling points are defined.

f. For sampling in areas with slope or hills with terrace, the entire field should be divided into smaller units such as upland and lowland (middle-land if necessary) and each unit should be sampled separately by any strategies discussed above.

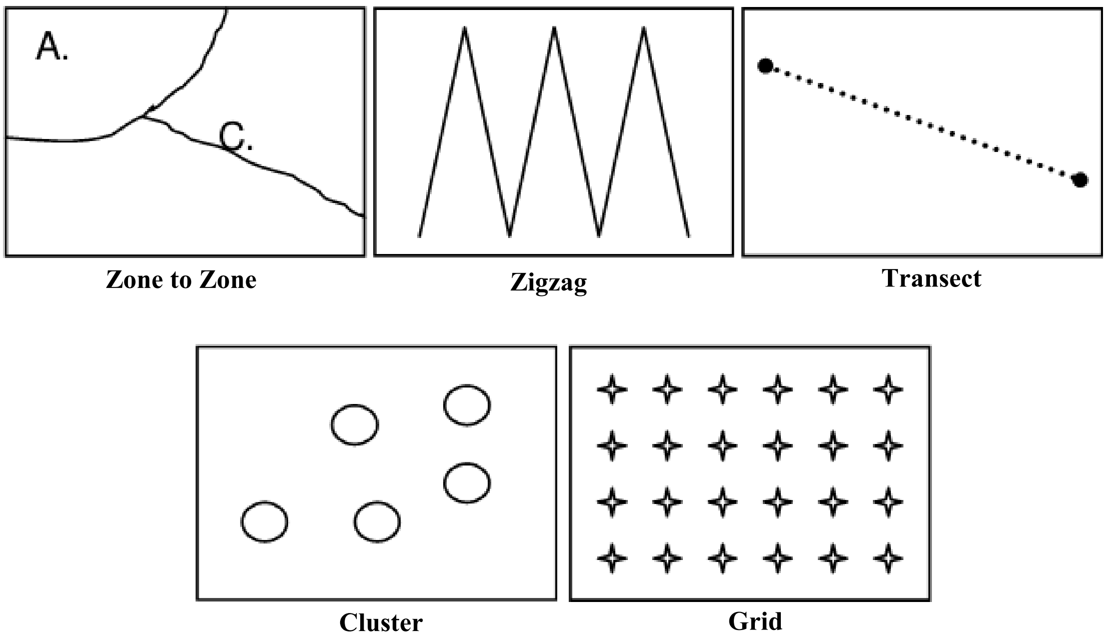

Figure 1. Commonly used soil sampling strategies

Making composite sample

- For making composite sample, collect small portion of soil up to desired depth (0-15 cm or greater) by means of suitable sampling tools from 15-20 well distributed spots (selection of spots is discussed in preceding section) from each individual sampling site.
- Mix together the soil collected from all the spots within one field thoroughly by hand on a clean piece of paper or polythene sheet or clear concrete floor.
- Reduce the bulk to about 500 g by quartering process. To achieve this spread the entire soil mass, divide into four quarters, discard two opposite one and remix the remaining two. Repeat the process until about 500 g soil is left behind (depicted in following figure).

- Use a separate, pre-labelled plastic bag for each sample. After filling with soil, securely tie up the bag.

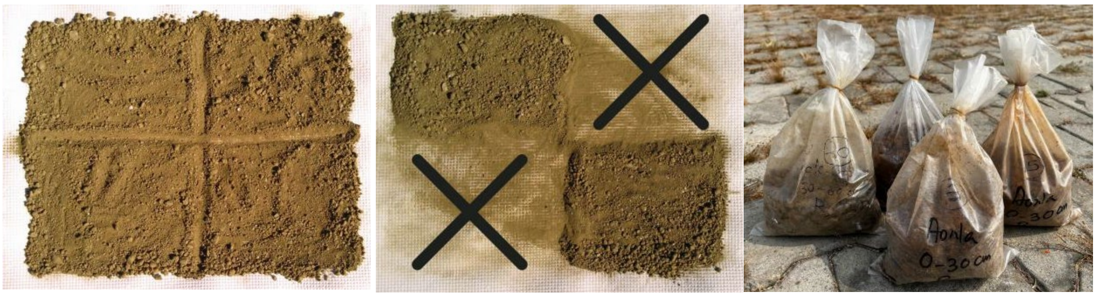

Figure 2. Composite sample preparation from bulk sample.

How are soil samples tested?

Soils are tested for pH, conductivity (EC), organic carbon, available nitrogen, phosphorus, and potassium, exchangeable cations and CEC, available sulphur and available micronutrients (iron, manganese, zinc, copper, boron). The soil has to be analyzed at least once *i.e.* before growth of plant started and if possible after harvesting of crop for knowing the fertilizer requirement before introducing a crop on to the field or applying fertilizer to an already existing plantation.

Estimation of soil organic carbon (SOC) stock

Soil organic carbon (SOC) refers to the carbon component of organic compounds found in soil organic matter (SOM). It is a critical indicator of soil health, fertility, and carbon sequestration potential. Estimating SOC stock helps in:

- Assessing soil quality and productivity
- Monitoring land use and management impacts
- Quantifying carbon sequestration for climate change mitigation

Key requirements

Soil organic carbon concentration

The proportion of carbon contained in soil, expressed as a percentage of dry soil weight (or g kg^{-1}).

Method A: Walkley–Black wet oxidation method

- Digest soil organic matter using $K_2Cr_2O_7$ (1 N) and concentrated H_2SO_4.
- Titrate the residual dichromate with $FeSO_4$ solution.
- Calculate SOC using:

$$\textbf{SOC (g kg}^{-1}\textbf{) = (B−S) × N × 0.003 × 1000/W}$$

Where,

B = Volume of $FeSO_4$ used in blank (mL)

S = Volume of $FeSO_4$ used in sample (mL)

N = Normality of $FeSO_4$ solution

W = Weight of soil (g)

0.003 = g of C equivalent to 1 mL of 1 N dichromate

Note: Apply a correction factor (1.33) for incomplete oxidation.

Method B: Dry combustion (Elemental Analyzer)

- Provides a precise measurement by combusting the sample at high temperature.
- More accurate but costlier than Walkley and Black method.

Bulk density (BD)

Bulk density (Mg m^{-3}) indicates the mass of soil per unit volume (including pore space). Soil coring method is used for estimation. It's essential for converting SOC concentration into stock per hectare.

Soil depth

SOC stock is often estimated for standard soil depths:

- 0–15 cm (surface)
- 15–30 cm (subsurface)
- Deeper layers for agroforestry systems (e.g., up to 100 cm)

Computation of SOC stock

SOC stock is the amount of organic carbon stored in a given soil volume (Mg C ha^{-1}). It is calculated using the following formula:

$$\textbf{SOC stock} = \textbf{SOC} \times \textbf{BD} \times \textbf{Depth} \times \textbf{10}$$

Where,

SOC (g kg^{-1}) = Organic carbon concentration

BD (Mg m^{-3}) = Bulk density

Depth (m) = Thickness of soil layer

The factor 10 converts units to Mg C ha^{-1}

For example,

Parameter	**Value**
SOC (g kg^{-1})	12.0
BD (Mg m^{-3})	1.35
Depth (m)	0.30

$$\textbf{SOC stock} = 12 \times 1.35 \times 0.30 \times 10 = 48.6 \text{ Mg C ha}^{-1}$$

Tree biomass and biomass carbon stock estimation

Tree biomass represents the total mass of living plant material above and below ground. Estimating biomass and its carbon content is fundamental for assessing carbon sequestration, ecosystem productivity, and the contribution of forestry and agroforestry systems to climate-change mitigation. This chapter provides concise, field-ready guidelines for forestry professionals and researchers to estimate tree biomass and carbon stock using standard measurement protocols and empirical models.

Concepts and definitions

Term	**Definition**
Biomass	The total dry weight of living plant material in a given area, expressed as Mg ha^{-1} (1 Mg = 1 ton).
Carbon stock	The amount of carbon stored in biomass, soil, and dead organic matter.
Aboveground biomass (AGB)	Biomass of stems, branches, leaves, and other living parts above the soil surface.
Belowground biomass (BGB)	Biomass of living roots.
Carbon pool	A reservoir that has the capacity to accumulate or release carbon.
Carbon fraction (CF)	The proportion of biomass that is carbon, usually 0.47 (IPCC 2006).

Biomass estimation methods

a. Destructive method

- Felling and direct weighing of trees, then drying sub-samples to determine dry weight.
- Highly accurate but destructive, time-consuming, and not suitable for protected forests.

b. Non-destructive/allometric method

- Uses tree metrics such as diameter at breast height (DBH), total height (H), and wood density (ϱ).
- Based on allometric equations derived from destructive sampling studies.

c. Remote sensing and modelling

- Biomass estimation from satellite data calibrated with field measurements.
- Useful for regional or national-scale assessments.

Field measurement protocols

Plot design

- Forest systems: circular plots of 0.1 ha (radius = 17.84 m).
- Agroforestry systems: rectangular plots (e.g., 20 × 50 m).
- GPS coordinates should be recorded for each plot.

Tree measurements

Parameter	Description	Instrument
DBH (cm)	Diameter measured at 1.37 m above ground	Diameter tape
Height (m)	Total height of tree	Altimeter, hypsometer or clinometer
Wood density (ϱ)	Oven-dry mass / green volume	From literature or wood samples

Sample data sheet

Tree No.	Species	DBH (cm)	Height (m)	ϱ (g cm⁻³)
1	*Tectona grandis*	32.4	19.2	0.62
2	*Shorea robusta*	28.6	17.8	0.74
3	*Acacia auriculiformis*	23.7	15.4	0.67
4	*Dalbergia sissoo*	30.1	16.9	0.78
5	*Mangifera indica*	38.5	13.5	0.57

Calculation procedures

3.2.1. Aboveground biomass (AGB)

Use the Chave et al. (2014) moist-tropical model: $\mathbf{AGB = 0.0673 \times (\varrho D^2 H)^{0.976}}$

Where,

ϱ = wood density (g cm^{-3})

D = DBH (cm)

H = height (m)

Belowground biomass (BGB)

Estimated using Cairns et al. (1997): $BGB = 0.489 \times (AGB)^{0.89}$

Total biomass and carbon stock

$$\mathbf{TB = AGB + BGB}$$

$$\mathbf{Biomass\ C = TB \times CF}$$

Where, CF = 0.47 (IPCC 2006).

Example calculation

Species	DBH (cm)	H (m)	ϱ	AGB (kg tree⁻¹)	BGB (kg tree⁻¹)	TB (kg tree⁻¹)	Carbon (kg tree⁻¹)
T. grandis	32.4	19.2	0.62	474.1	180.8	654.9	307.8
S. robusta	28.6	17.8	0.74	443.7	172.6	616.3	289.7
A. auriculiformis	23.7	15.4	0.67	296.8	124.9	421.7	198.2
D. sissoo	30.1	16.9	0.78	429.3	168.0	597.3	280.7

M. indica	38.5	13.5	0.57	552.5	201.5	754.0	354.4
Mean per tree	30.7	16.6	—	**439.3**	**169.6**	**608.9**	**286.2**

If there are 200 trees ha^{-1}:

608.9 kg×200=121780 kg ha^{-1} = 121.8 Mg ha^{-1}(total biomass)

Carbon=121.8×0.47=57.25 Mg C ha^{-1}

Uncertainty and error sources

Source	**Description**	**Mitigation**
Measurement errors	Inaccurate DBH or height readings	Calibrate instruments, repeat measurements
Equation selection	Using unsuitable models for forest type	Use region-specific equations
Wood density	Variation among species	Use local or species-level data
Sampling design	Too few plots or poor spatial representation	Stratify by land-use type and stand age

Summary

Accurate assessment of soil properties, biomass, and carbon stocks is essential for understanding the ecological and climate benefits of agroforestry systems. By applying standardized soil sampling procedures, using robust allometrics for biomass estimation, and following reliable carbon conversion and accounting guidelines, practitioners can generate data that are both credible and comparable across sites and projects. These skills not only support scientific monitoring but also strengthen the evidence base required for climate finance mechanisms, carbon offset programs, and sustainable land management initiatives. As interest in nature-based climate solutions and regenerative agricultural practices continues to grow, the ability to quantify carbon benefits confidently becomes increasingly important for researchers, extension workers, and agroforestry professionals. Overall, developing strong competencies in these measurement and accounting techniques empowers practitioners to make informed decisions, optimize agroforestry interventions, and contribute meaningfully to climate change mitigation and long-term landscape sustainability.

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Nursery Management for Productivity Optimization in Agroforestry Systems

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Introduction

Agroforestry systems, which integrate trees with crops, livestock, or other agricultural enterprises, depend primarily on the availability of high-quality planting material. In this context, nursery management serves as the mainstay of successful agroforestry interventions, influencing not only the establishment and survival of tree seedlings but also the long-term productivity and ecological benefits of the system. A well-planned and scientifically managed nursery ensures a consistent supply of healthy, vigorous, and genetically superior seedlings that can withstand diverse field conditions. This makes nursery management a critical component in optimizing productivity, enhancing system resilience, and improving the overall performance of agroforestry models across varied agro-climatic regions.

The importance of nursery management in agroforestry lies in its ability to control and optimize the early stages of plant growth i.e. germination, root development, and initial establishment. By providing favourable conditions such as suitable growing media, appropriate irrigation, adequate shading, and effective pest and disease management, nurseries significantly enhance the survival and growth rates of seedlings after transplantation. Quality planting material plays a central role in this process, as it directly determines how well trees perform in the field. High-quality seedlings possess well-developed root systems, balanced shoot growth, structural sturdiness, and higher tolerance to biotic and abiotic stresses.

The emphasis on nursery management also aligns closely with broader developmental goals, including sustainability, climate resilience, and livelihood enhancement. Agroforestry systems planted with high-quality, resilient seedlings contribute significantly to carbon sequestration, soil health improvement, biodiversity conservation, and microclimate regulation. These ecological benefits strengthen the capacity of farming landscapes to cope with climate variability, droughts, and environmental degradation. At the same time, efficient nurseries generate employment opportunities, particularly for rural youth and women, and supply planting material that enables farmers to diversify income sources and enhance household resilience.

Planning and Establishment of a Nursery

Establishing a nursery is a strategic process that requires careful planning, scientific understanding, and efficient resource utilization. A well-designed nursery ensures the continuous production of healthy, vigorous, and disease-free planting material that can support large-scale agroforestry interventions. Proper planning minimizes operational challenges, enhances seedling quality, and enables timely supply of species required for varied agroforestry systems. The following sections discuss the critical aspects involved in planning and establishing a nursery:

Criteria for Selecting a Nursery Site

A suitable nursery site should be easily accessible, ideally located near roads, markets, and plantation areas to minimize travel time and costs. There should be assured irrigation facility. The soil must be fertile, light to medium-textured, well-drained, and easy to work. Slightly elevated land with gentle slopes is preferred, as it enhances natural drainage and reduces the risk of waterlogging and disease. The site should receive adequate sunlight for robust plant growth, with provisions for creating shade structures when necessary.

Types of Nurseries

Nurseries are established with specific objectives that guide their structure, scale, and operational strategies. To meet these diverse objectives, nurseries can be classified into several types. Temporary nurseries are short-term, low-cost setups created for specific initiatives such as watershed projects, roadside plantations, or time-bound afforestation drives, and are particularly useful in remote locations where transporting seedlings is difficult. In contrast, permanent nurseries are well-established, long-term facilities equipped with infrastructure like bore wells, storage rooms, and shade houses, enabling year-round seedling production; these are commonly managed by research institutions, forest departments, and large farms. Commercial nurseries serve as profit-oriented enterprises that produce a diverse range of fruit, ornamental, forestry, and medicinal species, focusing heavily on quality, branding, and customer satisfaction to meet market demands. Community nurseries, operated by local communities, SHGs, FPOs, or village institutions, play a vital role in supplying affordable seedlings, generating employment, especially for women and strengthening grassroots involvement in agroforestry and greening programmes. At the most advanced level, hi-tech nurseries employ modern innovations such as mist chambers, polyhouses, automated irrigation, climate-controlled units, and root trainers, making them ideal for large-scale propagation of clonal material, grafted plants, and sensitive species while ensuring uniform growth, high survival rates, and round-the-year production. Collectively, these nursery types form an integrated system that supports sustainable plantation efforts, rural livelihoods, and ecological restoration.

Layout Planning and Infrastructure Requirements

A scientifically planned layout not only enhances productivity but also minimizes labour, reduces losses, and supports healthy seedling development. Zoning of the nursery area is the first critical step, dividing the space into functional units such as seed sowing and germination beds, transplant beds or containerized seedling sections, hardening yards for acclimatization, and mother blocks for clonal and vegetative propagation. Specialized propagation structures, including shade houses, mist chambers, and polyhouses-support sensitive species and ensure high-quality plant production. Additional essential zones include compost pits, manure preparation areas, well-designed irrigation points, storage rooms for inputs and tools, and a small office space for record-keeping and management. A nursery should have all infrastructures to support quality seedling production.

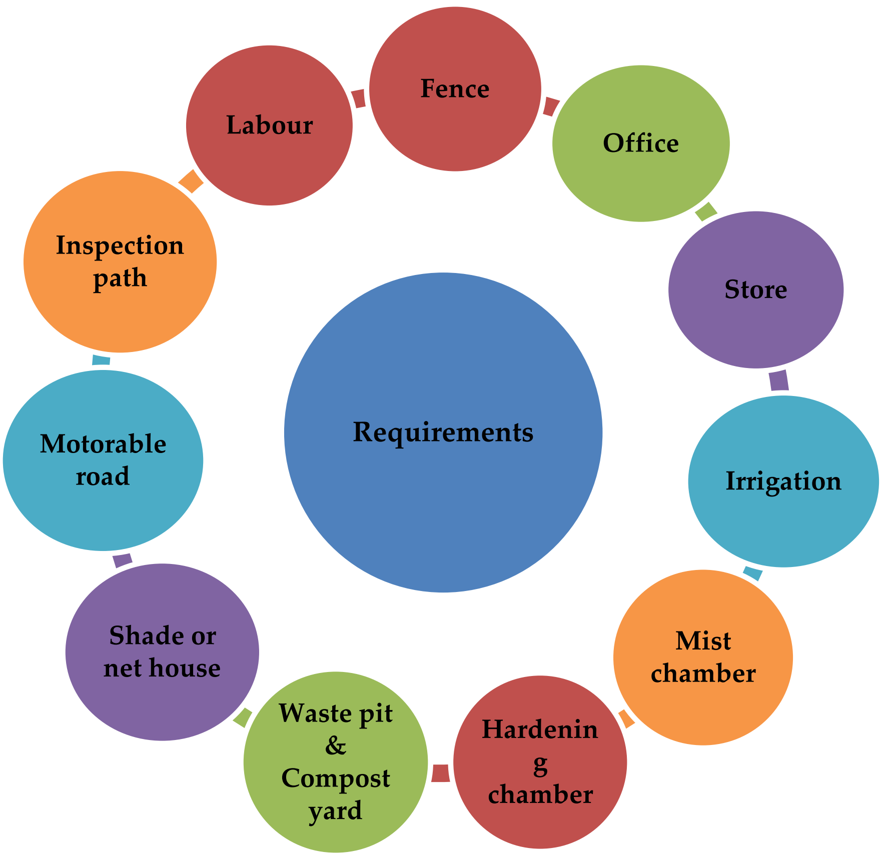

Figure 1. Important requirements for the establishment of the nursery

Strong and reliable infrastructure adds to the nursery's long-term efficiency, this includes secure fencing to protect against animals and unauthorized access, scientifically designed irrigation systems such as sprinklers, drip lines, hosepipes, or misting units, and shade structures. Dedicated storage areas for seeds, fertilizers, tools, and containers, along with potting sheds for preparing growing media, ensure organized operations and reduce wastage.

Resource Planning

Effective resource planning ensures uninterrupted nursery operations, optimizes costs, and enhances overall productivity. Properly trained labour improves efficiency, enhances propagation success, and reduces seedling mortality. Securing high-quality inputs is another cornerstone of nursery success. These include certified seeds, healthy cuttings, rootstocks, fertilizers, plant protection chemicals, and components of growing media such as soil, sand, compost, cocopeat, and vermicompost. Ensuring their availability in sufficient quantity prevents delays and maintains production schedules. A nursery also needs a steady supply of materials and equipment such as polythene bags, root trainers, trays, pots, shade nets, tools such as spades, secateurs, pruning knives, sprayers and wheelbarrows etc. These resources form the foundation of a productive, well-managed, and sustainable nursery.

Site Preparation and Nursery Structures

A carefully prepared site minimizes risks such as waterlogging, poor drainage, pest infestation, and restricted movement, while enhancing the microclimate required for successful plant growth. The important steps include thorough land clearing and levelling, effective drainage and water management, robust fencing and shade provision, strategic wind protection, well-designed internal pathways, and organized storage facilities. The choice of bed type, their dimensions, and their strategic arrangement directly influence water management, aeration, temperature regulation, and ease of nursery operations. A thoughtfully planned combination of raised, sunken, and flat beds, complemented by shade houses, polyhouses, mist chambers, and hardening yards, provides an optimum micro-environment for each developmental stage. These structures help manage species-specific requirements for moisture, light, humidity, and temperature, resulting in healthier seedlings, reduced mortality, and improved field performance.

Growing Media and Soil Management

An ideal growing medium must offer a balanced combination of physical, chemical, and biological properties that support robust plant growth. The integration of soil, sand, compost, vermicompost, cocopeat, and biochar helps create media that are wellaerated, well-drained, nutrient-rich, and biologically active. Equally important are soil sterilization techniques, including solarization, steam treatment, and biological amendments, which minimize pathogen load and ensure a disease-free environment. Effective soil and media management, therefore, not only improves seedling quality but also strengthens resilience during transplantation, contributing significantly to the sustainability and success of agroforestry nursery systems.

Nursery Containers and Root Management

The selection of appropriate containers-considering their size, material, drainage efficiency, and design directly affects water availability, aeration, and the direction of root growth during early development. Equally important is the adoption of sound root management practices to prevent deformities such as coiling, bending, or restricted branching, which can severely limit seedling stability and productivity after transplantation. Modern container systems such as root trainers, seedling trays, and biodegradable pots enable healthier root development by promoting natural air pruning, enhancing fibrous root formation, and minimizing transplant shock. When combined with timely root pruning, proper drainage management, and species-specific container choices, these systems ensure that seedlings establish faster, withstand environmental stress better, and contribute more effectively to sustainable agroforestry plantations.

Seed Handling and Storage

Sound seed procurement, meticulous handling, and scientific storage practices are essential to ensure the availability of superior planting material capable of withstanding diverse environmental stresses. By sourcing seeds from reliable and certified origins such as seed production areas, seed orchards, plus trees, or accredited institutional suppliers-nurseries can maintain genetic integrity and achieve uniform, vigorous seedling stands. Proper extraction, cleaning, and grading further enhance seed quality by removing contaminants, selecting the most viable seeds, and optimizing germination potential. Equally critical is the adoption of appropriate storage techniques tailored to seed behavior, whether orthodox, recalcitrant, or intermediate to preserve viability by regulating moisture, temperature, and humidity. Through a combination of scientifically guided procurement, precision processing, and efficient storage methods, nurseries can ensure a consistent supply of healthier seedlings, greater field survival, and long-term sustainability of agroforestry systems.

Seed Pre-treatments and Sowing Techniques

Seed pre-treatment and scientific sowing practices are vital steps for ensuring rapid, uniform, and vigorous germination in agroforestry nurseries. Many tree species exhibit natural dormancy mechanisms, making it essential to adopt appropriate dormancy-breaking methods such as scarification, stratification, and soaking. Scarification-whether mechanical, thermal, or chemical helps weaken hard seed coats, particularly in leguminous species, thereby facilitating quicker water uptake and embryo activation. Stratification mimics natural seasonal cues by exposing seeds to controlled cold or warm conditions. This method is especially useful for temperate fruit and nut species that have physiological or double dormancy. Simple soaking in clean water for 12 to 48 hours is effective for moderately hard-coated seeds. Once treated, seeds may be sown directly in the field or raised in nurseries for later transplanting. Direct sowing is advantageous for fast-growing or tap-rooted species but requires careful site management, while transplanting ensures better control over germination, uniform growth, and early seedling selection for high-value species such as *Santalum album.* Proper sowing depth around 2-3 times the seed diameter along with adequate spacing in beds or containers prevents overcrowding, minimizes damping-off, and supports healthy early growth. Post-sowing care, including regulated watering, shade management, disease control, timely weeding, and gradual hardening, enhances seedling vigour.

Vegetative Propagation Techniques

Techniques such as cuttings, layering, grafting, and budding allow rapid and reliable multiplication of elite genotypes while preserving desirable traits such as fast growth, straightness, disease resistance, and superior wood or fruit quality. Stem, semi-hardwood, and hardwood cuttings of species like Melia dubia, Gliricidia sepium, Eucalyptus, and Populus root readily under controlled humidity, supported by auxin treatments (IBA/NAA) and mist-bed environments. Grafting and budding techniques are widely used in fruit species to combine the vigour of rootstocks with the desirable fruiting traits of elite scions, ensuring early bearing and uniform orchard establishment (mango, aonla, ber, guava, and citrus). Clonal propagation has become a cornerstone of modern agroforestry. The use of plant growth regulators (auxins, cytokinins) and bio-stimulants such as humic substances, seaweed extracts, and PGPR further enhances rooting, shoot proliferation, and stress tolerance, making vegetative propagation more efficient and cost-effective. Advanced micro-propagation and tissue culture techniques allow year-round production of disease-free, uniform, and elite planting stock of many plant species suitable for agroforestry such as bamboo, eucalyptus, poplar, and various fruit crops.

Irrigation and Fertilization Management in Nursery

Proper irrigation and balanced nutrition are vital for healthy, vigorous seedlings. Irrigation methods vary: manual, sprinkler, drip, or mist systems depending on nursery scale and species. Organic amendments (compost, vermicompost, cocopeat, biochar) and biofertilizers enhance soil health and nutrient uptake, while foliar sprays correct deficiencies quickly. Combined, precise irrigation and fertilization produce uniform, resilient seedlings ready for successful field establishment.

Plant protection

Seedlings in their early stages are highly sensitive to insect pests, diseases, and environmental stresses; therefore, adopting a comprehensive protection strategy is vital. Effective management integrates strict hygiene practices with an Integrated Pest Management (IPM) approach, combining cultural, mechanical, biological, and need-based chemical methods to keep pest populations below harmful levels. Common nursery threats include defoliators, sap-sucking insects, borers, and root feeders, along with major diseases such as damping-off, leaf spots, root and collar rots, powdery mildew, and bacterial infections. Physiological disorders caused by nutrient deficiencies, water stress, and poor aeration may also mimic disease symptoms, making accurate diagnosis essential. Cultural practices like maintaining proper spacing, using sterilized media, and ensuring good ventilation help prevent disease outbreaks, while mechanical tools such as sticky traps and manual removal aid in early pest suppression. Biological agents including Trichoderma and beneficial insects offer eco-friendly control options, complemented by botanical pesticides like neem oil. Chemical pesticides are used only as a last resort and in recommended doses to minimize environmental impact. Maintaining high nursery hygiene through regular cleaning, sanitation of tools and containers, and exclusion of infected material significantly reduces pathogen entry and ensures a sustainable, healthy nursery environment.

Table 1. Management of important disease in nursery

Disease	Causal organism	Symptoms	Management
Damping off	*Pythium, Phytophthora, Fusarium*	The infection takes place at the base of the young stems or the soil level. Tissues become water soaked and rapidly collapse thus topping the seedlings.	Drench the seedling beds with Dithane M-45 (0.01%; 1g/10 liters of water). Repeat the treatment two times at 20 days intervals.

Wilt	*Fusarium*	Start with the yellowing of leaves. Affected seedlings will die within 48 hours	Avoid excess watering of the beds. Use 0.01-0.02% solution of Bavistin/ Dithane Z-78 at monthly intervals.
Root-Rot	*Fusarium, Phytophora* and *Rhizoctonia*	The plant starts wilting initially, dark spot on the stem, leaves start yellowing and roots completely rot	It can be controlled by Dithane M-45 or Bavistin at monthly intervals.
Powdery Mildew	*Uncinula* spp	White chalky appearance can be observed on the upper surface of the leaves which spread through spores very rapidly.	It can be controlled by sulphur-based fungicides. Karathane at 0.05% spray on leaves at the interval of 20-30 days.
Collar-Rot	*Botryodiplodia theobromae*	It starts with a collar with small spots over the collar. Black pycnidia can be observed in an upward direction.	It can be controlled by soil drenching with Dithane Z-78 (0.2%).

Table 2. Management of important insect pest of the nursery

Insect pest	**Symptoms**	**Management**
Cutworms	Larvae cut off young seedlings soon after germination usually in March-April. Feed on young seedlings during night, cutting them off, at the ground level.	• Collection and destruction of larvae hidden. • Digging in early winter exposes the hibernating larvae to frost. • Proper weeding
Termites	Termites attack mainly the upper 20 cm of the soil layer. Termites feed on the tap roots and result in tapering and complete severance of the root system. The seedlings become yellow and wilt and die. One-year-old seedlings are severely damaged.	• The site should be free from wood debris, termite nests, etc. • Strong silvicultural practices should be followed which promote vigorous growth.

White grubs	They feed on the roots and rootlets of seedlings. They disrupt the soil around the growing plants and disturb the root system and cause loss of moisture necessary for root growth. Roots become dry and cause the death of the seedling.	• Deep ploughing of nursery beds in winter. • Sowing should be done when the beetles are not on the wings. • Use of light traps during adult emergence from 7.30 pm onwards for about 20 days.
Defoliators	Leaf-feeding beetles damage the foliage of nursery stock. Adult beetles are polyphagous feeders of foliage, flowers and fruits. The larvae feed on the inner surface of the leaf. The infected leaf falls or remains suspended. Some larvae feed on leaf tissues except the larger veins.	• A spray of monocrotophos (0.036%) gives a good result in controlling the defoliators. • A foliar spray of Endosulfan, Fenitrothion, or Malathion (0.1-0.2%) water emulsion can also be used for effective control of defoliators.

Weed Management Strategies

Effective weed management begins with preventive measures such as using clean, sterilized growing media, maintaining well-sanitized surroundings, and applying mulches to minimize open soil exposure. Mechanical methods like regular hand weeding, hoeing, and shallow cultivation help prevent weed establishment. Cultural strategies, including maintaining optimal shade levels and regulating irrigation, significantly reduce weed growth by creating conditions unfavorable for their emergence. Chemical control is used only as a last resort in nursery settings, with pre-emergence herbicides like pendimethalin limited to non-seedling areas and post-emergence herbicides restricted to pathways and non-plant zones to avoid accidental drift. By integrating preventive, mechanical, cultural, and minimal chemical interventions, nurseries can maintain weed-free, healthy environments conducive to robust seedling growth.

Seedling Growth Monitoring and Quality Assessment

Seedling vigor and quality are assessed through key growth indicators like height, collar diameter, leaf number, root length and volume, and biomass. Integrated indices like Seedling Vigour Index (SVI), Dickson's Quality Index (DQI), and Leaf Area Index (LAI) provide comprehensive evaluation of performance, uniformity, and treatment effects. Physiological measures such as root-to-shoot ratio, sturdiness quotient, and chlorophyll content predict field establishment, drought tolerance, and overall resilience. Seedling certification and adherence to quality standards are vital for large-scale agroforestry programs, ensuring that planting material is genetically pure, healthy, and capable of sustained field performance. Certification systems emphasize source-identified or certified seed origin, freedom from pests and diseases, optimal species-specific height and collar diameter, healthy, non-deformed roots, and the use of approved media and containers. Hardening acclimatizes seedlings to field conditions by gradually reducing irrigation, increasing light exposure, moderating nutrients, improving ventilation, and strengthening stems. Properly hardened seedlings show compact growth, robust roots, and greater tolerance to heat, drought, and transplant shock, ensuring strong field establishment.

Nursery Economics and Resource Optimization

Economic planning is essential for running a cost-efficient and sustainable nursery. By understanding input, labour, and infrastructure costs, managers can budget accurately, minimize waste, and enhance profitability. Strong financial planning through production forecasting, annual budgets, per-seedling cost calculations, and break-even analysis ensures smooth operations and supports better decision-making. Improving labour efficiency and adopting mechanization such as soil mixers, tray fillers, automated transplanting units, and irrigation timers reduces costs and improves seedling uniformity. Together, these practices strengthen nursery productivity, profitability, and long-term resilience.

Climate-Smart and Innovative Nursery Technologies

Climate-smart technologies are transforming nurseries into efficient, resilient, and sustainable production systems. Protected structures like polyhouses, shade houses, and mist chambers create controlled microclimates that reduce losses and improve seedling quality, while solar-powered pumps and lighting offer energy-efficient solutions. Advanced media such as biochar mixes, perlite, and biodegradable blocks enhance aeration, moisture retention, and nutrient use. Tools like drones, automated pot fillers, and diagnostic sensors further improve accuracy and efficiency. Complemented by climate-smart practices such as rainwater harvesting, water recycling, organic pest control, and low-carbon operations, these innovations boost productivity, improve seedling survival, and strengthen nursery resilience in a changing climate.

Propagation of some Agroforestry Tree Species

Agroforestry systems integrate a diverse array of tree species, each having unique propagation requirements, growth behavior, and nursery management needs.

Understanding species-specific nursery techniques is essential for producing high-quality planting material that ensures better survival, productivity, and system optimization.

Table 3. Commonly used propagating methods

Species	Common Name	Propagation method	Time of sowing (Month)	Normal germination period (Days)
Acacia catechu	Khair	Seed	February-April	40
Adina cordifolia	Haldu	Seed	March-May	30
Aegle marmelos	Bael	Seed/Vegetative propagation	May-June	21
Anogeissus latifolia	Axlewood	Seed	April-May	15
Artocarpus heterophyllus	Jackfruit	Seed/ Softwood grafting (Cleft grafting)	June-August	21
Buchanania cochinchinensis	Chironji	Seed	May-July	15-30
Dalbergia sissoo	Shisham	Seed	February-March	10-15
Madhuca indica	Mahua	Seed	July-August	15-20
Michaelia champaca	Champa	Seed	August - October	45
Phyllanthus emblica	*Aonla*	Seed/ Vegetative	March	30
Pongamia pinnata	Karanj	Seed	July-August	30
Pterocarpus marsupium	Indian Kino tree	Seed	February - March	14-56
Pterocarpus santalinus	Red sanders	Seed	May-June	35
Terminalia arjuna	Arjun tree	Seed	April-May	12-13

Terminalia bellirica	Behera	Seed	June-July	14-30
Terminalia chebula	Harad	Seed	June-July	90

Nursery's Role in Large-Scale Agroforestry Expansion

Nurseries are key to large-scale agroforestry, providing good-quality, site-suitable, and affordable planting material needed for landscape restoration and climate-resilient livelihoods. As agroforestry gains global importance for improving soil health, boosting farm incomes, mitigating climate change, and rehabilitating degraded lands, the need for efficient, well-connected nurseries becomes even more critical. Community nurseries and self-help group led enterprises decentralize seedling production, create local employment, empower women and tribal communities, and provide regionally adapted planting material with higher field survival. Government initiatives such as the National Agroforestry Policy, Sub-Mission on Agroforestry (SMAF), National Bamboo Mission, MGNREGS, and technical guidance from ICAR - Institutions, SAUs, CAUs and KVKs further strengthen this ecosystem through training, accreditation, and access to elite germplasm. Strong linkages among farmers, FPOs, and the private sector build efficient supply chains and market-responsive nurseries capable of meeting rising demand for fruit, fodder, timber, bamboo, and medicinal species. Farmers gain access to affordable seedlings and local advisories; FPOs support bulk procurement and cluster-based planting; and private companies contribute advanced propagation techniques, buy-back arrangements, and partnerships in commercial forestry and carbon projects. Thus, nurseries become powerful engines for promoting agroforestry at larger scale.

Conclusion

Nursery management is the strength of successful agroforestry, supporting large-scale plantations, better livelihoods, and ecological restoration. The quality and availability of diverse planting material directly affect productivity, species performance, and long-term sustainability. A well-managed nursery improves seedling survival, boosts field performance, and strengthens the overall productivity, resilience, and profitability of agroforestry systems.

Plant tissue culture for sustainable agroforestry: ensuring quality planting material production

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Introduction

Plant tissue culture (PTC) is the in vitro aseptic technique of culturing plant cells, tissues, or organs under defined nutritional and environmental conditions to regenerate whole plants. It exploits the totipotency of plant cells, allowing rapid clonal propagation, production of disease-free plants, genetic improvement, and conservation of valuable germplasm for research, agriculture, horticulture, and forestry. This technique enables precise control over growth conditions, facilitating studies in plant development, breeding, and biotechnology. The fundamental principle is totipotency, which means any living plant cell contains all the genetic information required to regenerate a whole plant. Tissue culture enables the propagation of genetically uniform, disease-free, and high-quality planting material rapidly and at large scale, overcoming limitations of traditional propagation methods such as slow multiplication rates, seed dormancy, and poor seed viability.

In agriculture, horticulture and forestry, raising Quality Planting Material (QPM) is key for ensuring crop uniformity, vigour, and productivity. Tissue culture provides an effective route to produce such material, customizable for various crop species including fruits, vegetables, spices, and medicinal plants. It supports rapid multiplication of elite genotypes, production of virus-free plants through meristem culture, and enables germplasm conservation.

Historical Perspective

The concept of plant tissue culture dates back to the early 20th century. Gottlieb Haberlandt first suggested the idea in 1902, but practical success came after the development of sterile culture techniques and nutrient media. The Murashige and

Skoog (MS) medium formulation in 1962 revolutionized plant tissue culture by providing a balanced nutrient medium optimized for diverse plant species.

Table 1. Historical milestones in the field of PTC

Year	Milestone Event	Significance
1902	Haberlandt proposed totipotency	Concept of plant cell totipotency foundational for PTC
1939	Gautheret cultured carrot root cambium	First continuously growing tissue cultures
1952	Morel and Martin achieved virus-free plants by meristem culture	Important for producing disease-free plants
1957	Skoog and Miller defined auxin-cytokinin ratio effects	Explained hormonal control of shoot/root formation
1960	Cocking isolated and cultured protoplasts	Enabled cell fusion and genetic manipulation
1966	Guha and Maheshwari produced haploid embryos	Advanced genetic and breeding research
1978	Zelcer, Aviv, and Galun developed protoplast fusion	Enabled somatic hybridization
1981	Larkin and Scowcroft described somaclonal variation	Revealed genetic variability in tissue cultures
2000s	Genetic engineering tools integrated with PTC	Revolutionized plant biotechnology
2024	Establishment of modern large-scale tissue culture labs	Supported sustainable agriculture and biotech innovation

Table 2. Major terminologies in used in the plant tissue culture and biotechnology

Term	Description
Explant	A small piece of plant tissue (leaf, stem, root, meristem, etc.) used to initiate culture under sterile conditions.
In vitro	Latin for "in glass"; refers to plant growth in controlled, artificial conditions outside the living organism.
Culture Medium	Nutrient-rich formulation containing minerals, vitamins, carbon source (e.g., sucrose), and plant growth regulators for tissue development.
Murashige and Skoog (MS) Medium	A widely used basal medium for plant tissue culture formulated by Murashige and Skoog (1962).

Aseptic Conditions	Sterile working environment to prevent microbial contamination of plant cultures.
Callus	Unorganized mass of undifferentiated cells produced during initial culture stages.
Differentiation	Process by which unspecialized cells develop into specialized cell types or organs.
Dedifferentiation	Reversion of mature, specialized plant cells into an undifferentiated, meristematic state capable of division.
Redifferentiation	Development of new specialized structures (like shoots or roots) from dedifferentiated cells or callus tissue.
Organogenesis	Formation of organs such as shoots or roots from cultured explants or callus tissue.
Somatic Embryogenesis	Formation of embryo-like structures from somatic (non-gametic) cells that can regenerate into full plants.
Micropropagation	Rapid clonal multiplication of elite genotypes using in vitro techniques.
Plant Growth Regulators (PGRs)	Chemical compounds (e.g., auxins, cytokinins) that influence cell division, elongation, and differentiation in culture.
Auxins	Hormones promoting cell elongation and root formation (e.g., IAA, NAA, IBA, 2,4-D).
Cytokinins	Hormones stimulating cell division and shoot induction (e.g., BAP, Kinetin, Zeatin).
Subculture	Transfer of growing tissue to fresh medium to maintain or multiply the culture.
Rooting	Induction of roots on in vitro regenerated shoots, usually by auxin-enriched media.
Acclimatization	Gradual adaptation of tissue-cultured plants to external environmental conditions before field establishment.
Contamination	Unwanted growth of bacteria, fungi, or yeast in the culture medium.
Clonal Fidelity	Genetic uniformity of micropropagated plants compared to the donor plant.
Hardening	Physiological strengthening of plantlets before transplantation into soil conditions.

Cryopreservation	Long-term storage of plant tissues or germplasm in liquid nitrogen (−196°C) to preserve genetic resources.
Totipotency	Ability of a single plant cell to regenerate into a whole plant under appropriate culture conditions.
Protoplast	Plant cell without a cell wall, used for fusion, genetic transformation, or somatic hybridization studies.
Somatic Hybridization	Fusion of two protoplasts from different species or varieties to combine desirable traits.
Genetic Transformation	Introduction of foreign DNA (gene) into plant cells to alter genetic makeup.
Agrobacterium-mediated Transformation	A method using *Agrobacterium tumefaciens* to transfer desired genes into plant genomes.
Bioreactor	Controlled vessel used for large-scale plant tissue culture or cell suspension cultures.
Synthetic Seed	Artificially encapsulated somatic embryo or shoot tip capable of developing into a plant under suitable conditions.
Elongation	Phase where regenerated shoots or roots increase in length before rooting or hardening.

Major types of plant tissue culture

The type of plant tissue culture is mainly decided based on the explant source (which plant part is used) and the intended morphogenetic response (organogenesis or embryogenesis). Additionally, culture conditions like medium composition, physical environment, and the purpose of the culture also influence the classification.

Table 3. Types of PTC

Types	**Description**
Seed Culture	Culturing seeds in vitro to grow healthy seedlings, useful for species with dormancy issues.
Meristem Culture	Using apical or shoot meristems to produce disease-free plants, commonly for virus elimination.
Callus Culture	Culturing an undifferentiated mass of cells (callus) for plant regeneration and genetic work.

Cell Suspension Culture	Growing single cells or small clumps in liquid media for rapid multiplication and metabolite production.
Anther Culture	Culturing anthers or pollen to produce haploid plants, speeding breeding via doubled haploids.
Protoplast Culture	Culturing cell-wall-less cells for somatic hybridization and genetic modification.
Embryo Culture	Culturing excised embryos for hybrid rescue and overcoming seed dormancy or incompatibility.
Organ Culture	Culturing specific plant organs like roots or shoots for studying development or propagation.
Somatic Embryogenesis	Formation of embryos from somatic cells, important for synthetic seed production and cloning.
Micropropagation	Large-scale clonal propagation using tissue culture techniques to produce uniform plants rapidly.

Ideal PTC laboratory layout

A well-organized laboratory is crucial to ensure aseptic conditions and successful tissue culture operations. The lab is divided into distinct areas:

a. Washing & Storage Area

- Equipped with large sinks resistant to acids and alkalis, running hot and cold water.
- Facilities for soaking, washing glassware, and sterilizing instruments.
- Storage cabinets that keep sterile glassware dust-free.

b. Media Preparation Area

- Spacious benches for weighing chemicals and mixing solutions.
- Equipment: analytical balances, pH meters for adjusting medium pH, magnetic stirrers for uniform solution mixing, water baths, hot plates.
- Stock chemical storage in refrigerators/freezers to preserve vitamins, hormones.
- Autoclave or pressure cooker for sterilization of media and instruments.

c. Aseptic Transfer Area

- Dedicated laminar flow hood or inoculation chamber maintaining a sterile environment by filtering air through HEPA filters.
- UV lamps for surface sterilization of working surfaces and instruments.
- Used for inoculating explants onto media and subculturing without contamination.

d. Culture Rooms

- Controlled temperature (25±2°C), humidity, and light (16 hr photoperiod, 1000-1500 lux), ensuring optimal growth.
- Racks/shelves for placing culture vessels.
- Air circulation with filtered ventilation to minimize microbial contamination.

e. Observation and Acclimatization Area

- Microscope workstations for culture assessment.
- Hardening/greenhouse area where rooted plantlets adapt gradually to external environment before field transfer.

Safety Considerations

- Fire extinguishers and first aid kits.
- Continuous power backup to maintain controlled conditions.

Tools used in the PTC lab

A plant tissue culture lab uses specialized tools and equipment to ensure aseptic conditions, accurate manipulation of plant material, and optimal growth of cultures. The following note summarizes the essential instruments and their functions in such laboratories.

- **Laminar Flow Hood:** Provides a sterile environment by directing filtered air across the work surface, preventing contamination during the handling of plant tissues. Its use is central during inoculation, explant transfers, and subculturing.
- **Autoclave:** Sterilizes glassware, culture medium, and tools using high-pressure steam, ensuring that all materials are free of microorganisms before use.
- **Culture Vessels:** Includes Petri dishes, test tubes, culture flasks, and bottles. These containers maintain aseptic culture conditions for the growth and multiplication of plant tissues.
- **Microscopes:** Used for the observation of cell differentiation, morphological changes, and contamination. Both standard bright-field and specialized microscopes (e.g., fluorescence) are commonly used.
- **Growth Chamber/Incubator:** Regulates temperature, humidity, and light to provide the optimal environment for plant tissue growth.
- **Hot Air Oven:** Used for dry sterilization of glassware and metal instruments, complementing the autoclave.
- **Centrifuge:** Separates plant cells or particles from liquid media during sample preparation and purification.
- **Refrigerator:** Stores media, chemicals, and explants at controlled temperatures to maintain stability and prevent degradation.

- **Distillation Unit:** Provides distilled water needed for media preparation and washing of glassware.
- **Shaker:** Facilitates suspension cultures by continuously agitating liquid media.

Ancillary Tools and Supplies:

- **pH Meter and Conductivity Meter:** Ensure the prepared media have the right chemical properties for sustaining plant growth.
- **Balances:** Precise measurement of chemicals and reagents for media preparation.
- **Sterile Glassware and Plasticware:** Such as beakers, graduated cylinders, and Erlenmeyer flasks are used for media preparation and culture maintenance.
- **Dissection Tools:** Includes forceps, scalpels, scissors, and pipettes for the manipulation, sectioning, and transfer of plant tissues.
- **Safety Gear (PPE):** Lab coats, gloves, masks, and caps to maintain cleanliness and protect from chemical exposure.
- **UV Sterilizer:** Often fitted in laminar flow cabinets to further reduce microbial contamination on work surfaces.
- **Labeling Supplies:** Essential for traceability of cultures (e.g., markers, labels, autoclave-resistant tapes).

Preparation of Solutions and Media

The choice and preparation of culture media are fundamental to the success of tissue culture work in the laboratory.

The nutrition media:

- Macronutrients: Nitrogen (N) in nitrate and ammonium forms, potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), and sulfur (S).
- Micronutrients: Iron (Fe) chelated with EDTA, manganese (Mn), zinc (Zn), boron (B), copper (Cu), molybdenum (Mo), cobalt (Co), iodine (I).
- Vitamins: Thiamine (B1), nicotinic acid (B3), pyridoxine (B6), and sometimes others to support enzymatic functions.
- Carbon Source: Typically, sucrose (20-60 g/L) as plant cells often lack photosynthesis capability *in vitro*.
- Organic Supplements: Amino acids, coconut milk, casein hydrolysate for species-specific needs.
- Plant Growth Regulators: Auxins (IAA, NAA, IBA, 2,4-D) for cell division and root induction; cytokinins (BAP, kinetin) for shoot proliferation; gibberellins and abscisic acid rarely used but for specific morphogenesis.
- Gelling Agents: Agar (0.7-1%), agarose, phytagel to solidify media.

Molar, percent, and X solutions

a. Molar solution: is one in which 1 litre of solution contains the number of grams equal to its molecular weight.

Example: To make up 100 ml of a 5M NaCl solution

= 58.456 (mw of NaCl) g × 5 moles × 0.1 liter

= 29.29 g in 100 ml mole liter

b. Percent solutions:

- Percentage (w/v) = weight (g) in 100 ml of solution
- Percentage (v/v) = volume (ml) in 100 ml of solution
- Example: To make a 0.7% solution of agarose in TBE buffer, weigh 0.7g of agarose and bring up the volume to 100 ml with the TBE buffer.

c. X solutions: Many enzyme buffers are prepared as concentrated solutions

- Eg. 5 X or 10 X (5 or 10 times the concentration of the working solution), and are then diluted so that the final concentration of the buffer in the reaction is 1 X.
- Example: To set up a restriction digestion in 25 ml, one would add 2.5 ml of a 10 X buffer, the other reaction components, and water for a final volume of 25 ml.

Standard NaOH Solution (0.1M/0.1N)

- Take 0.4g NaOH and dissolve gradually with 100ml sterile distilled water.

Standard HCl Solution (0.1M/0.1N)

- Dilute 9 ml of pure concentrated HCl to 1.0 l with distilled water in volumetric flask. Invert several times and transfer to a clean, dry bottle.

Preparation of PGR stock solution

To prepare a 1 mg/mL (1000 ppm) stock solution of a PGR, weigh 100 mg of the pure PGR powder.

- Add 3-5 mL of an appropriate solvent (e.g., distilled water, ethanol, or NaOH solution) to dissolve the powder completely.
- Once dissolved, transfer the solution to a 100 mL volumetric flask and add distilled or deionized water up to the 100 mL mark. Mix thoroughly.
- To prepare the culture medium with a final PGR concentration of 1 mg/L (1 ppm), add 1 mL of this stock solution to 1 liter of the culture medium.

The general formula to calculate the volume of stock solution needed is:

$$\textbf{Volume of stock (mL)} = \frac{\textbf{Desired final concentration(mg/L)} \times \textbf{Volume of medium(L)}}{\textbf{Stock concentration (mg/mL)}}$$

For example, to get 0.5 mg/L final PGR concentration in 500 mL medium with 1 mg/mL stock solution:

$$\textbf{Volume of stock (mL)} = \frac{\mathbf{0.5 \times 0.5}}{\mathbf{1}} = \mathbf{0.25\ mL}$$

Sterilization techniques

Here is a detailed descriptive methodology for each sterilization technique used in plant tissue culture:

Autoclaving (Moist Heat Sterilization): Materials such as culture media, glassware, and instruments are placed in the autoclave and exposed to saturated steam at 121°C under 15 psi pressure for 15 to 20 minutes. The moist heat denatures proteins and kills all forms of microbial life including spores, ensuring complete sterilization. After autoclaving, materials are allowed to cool in sterile conditions before use.

Dry Heat Sterilization: Glassware, powders, and heat-stable oils are sterilized by placing them in a hot air oven at 160-180°C for 1-2 hours. Dry heat oxidizes cellular components and dehydrates microbes, effectively killing them. This method is especially suitable for materials that cannot tolerate moisture or steam.

Flaming: This quick sterilization technique is used for small instruments like scalpels and forceps by briefly passing their tips through an open flame (e.g., Bunsen burner). The intense heat rapidly incinerates any contaminating microbes on the surface. Instruments are cooled before contact with explants.

Filter Sterilization: Heat-sensitive solutions such as plant growth regulators, vitamins, and antibiotics are sterilized by passing them through membrane filters with pore sizes typically 0.22 micrometers. This physically removes bacteria and fungi without affecting the chemical integrity of the solutions, which is critical for their biological activity.

Surface Sterilization of Explants: Plant tissues are rinsed sequentially with detergents, followed by sterilizing agents like 70% ethanol, sodium hypochlorite (bleach) solutions, or hydrogen peroxide for short exposure times to remove surface microbes. The explants are then rinsed with sterile distilled water to remove residual chemicals before culture initiation.

Air Sterilization: Work with cultures is performed inside laminar airflow hoods equipped with HEPA (High-Efficiency Particulate Air) filters. These filters remove airborne microbes and particles by blowing a continuous flow of sterile, filtered air across the work surface, preventing contamination from the laboratory environment during inoculation and subculturing.

Tyndallization: Used for sterilization of heat-sensitive culture media, this method involves heating the medium in boiling water (~100°C) for one hour on three consecutive days with incubation periods in between. This allows spores to germinate and be killed on subsequent heating cycles, ensuring sterilization without autoclaving.

Different stages of micropropagation

The plant tissue culture process involves several detailed stages essential for successful micropropagation and research:

Selection and Preparation of Explant: A suitable plant tissue (explant) like leaf, stem, meristem, or seed is carefully chosen from a healthy plant. This explant undergoes surface sterilization using agents like sodium hypochlorite or ethanol to eliminate microbial contaminants while preserving tissue viability.

Initiation or Establishment Stage: The sterilized explant is transferred aseptically to a sterile nutrient medium containing essential macronutrients, micronutrients, vitamins, a carbon source (usually sucrose), and specific plant growth regulators (PGRs) to stimulate initial cell division. This stage marks the beginning of in vitro growth, where cells recover and start proliferating.

Multiplication Stage: The growing explant or callus is subcultured onto fresh media with optimized hormone concentrations to stimulate rapid proliferation, resulting in increased number of shoots or callus mass. Cytokinins are often emphasized here to promote shoot proliferation.

Rooting/Regeneration Stage: Shoots produced in multiplication are transferred to rooting media containing a higher concentration of auxins, which induce root formation. Rooted plantlets are carefully developed for successful transition to soil.

Acclimatization/Hardening: The in vitro regenerated plantlets with shoots and roots are gradually adapted to ex vitro conditions by carefully reducing humidity and adjusting light and temperature in greenhouse or growth chambers. This phase ensures plantlets develop functional cuticles and robust physiology to survive natural environments.

Each step is critical and requires precise control of sterilization, nutrient medium composition, growth regulator balance, and environmental parameters like temperature, light, and humidity. Successful coordination of these phases leads to the regeneration of healthy, genetically stable plants suitable for agriculture, horticulture, forestry, or research applications.

Aseptic Techniques:

Principle: Precautions must be taken to prevent the entry of any microorganism at the time of transferring the surface sterilized explants on the nutrient medium (inoculation) using the sterilized instruments. For this reason, manipulation and transfer should ideally be carried out under aseptic condition. Starting from surface sterilization to inoculation, all operations should be done aseptically.

Procedure: A typical procedure of aseptic technique is given below:

- Put all the sterilized articles (media, instruments, glass goods etc.) for inoculation on the glass racks of the inoculation chamber. Alternatively, if laminar air flow is available, keep all articles on the table of air flow cabinet. Laminar air flow blows bacteria- free air over the working surface.
- Put on the switch of UV lamps of inoculation chamber for one hour before work. In case of laminar air flow, the power switch is put on and allows the air flow to blow air for at least 15 minutes before work.
- Put off the UV lamp before entering inside the inoculation chamber. Do not put off laminar air flow. The working glass table top of the inoculation chamber or the table of laminar air flow is swabbed with alcohol before starting work.
- Wear a clean apron and use a mask. Clean the hands with alcohol and dry it.
- Pour alcohol in a clean coupling jar and dip all instruments into it. Light the spirit lamp. Take the surface sterilized or aseptic plant material in a, sterile petri dish.
- Flame the neck of culture tube or flask and in quick succession remove the plug of glass vials. Transfer the tissue onto the medium and replace the closure. Each time, the instruments are passed through the flame of the spirit lamp.

Incubation of Culture:

Principle: High temperatures are likely to lead to dissociation of the culture medium and tissue damage while at very low temperatures tissue growth is slow. Again, some tissues grow well in dark while others need both light and dark conditions. Low humidity causes the quick desiccation of culture medium and high humidity is favourable for the contamination of culture medium. Therefore, cultures are incubated in a culture room where light, temperature and humidity are controlled. Basic procedure includes

- After inoculating the tissue onto the culture medium, cultures are incubated on culture rack at 25-28°C constant temperature.
- Culture tubes are placed at 30-45° inclined position. For this purpose a long wooden stick or an empty paper cover of fluorescence lamp is placed on the

middle of culture rack and lay the plugged end of the culture tube on the support.

- Illumination is provided by cool-white fluorescent light placed about 18 inches above the culture to give a light intensity of 4 – 10 x 103 lux for 16 hours.
- If light is not necessary, then put off the light and cover the whole rack with a black cloth.

Organogenesis

Organogenesis is the process of forming new plant organs such as shoots and roots during in vitro plant regeneration and is classified into two types: direct and indirect.

- **Direct Organogenesis** involves the development of shoots or roots directly from the explant tissue without an intervening callus stage. In this process, the explant's meristematic or adventitious cells differentiate directly into organized organs when cultured on suitable media with appropriate plant growth regulators. Direct organogenesis benefits include faster regeneration, lower chances of genetic variation, and maintenance of true-to-type clones, making it ideal for clonal propagation and production of virus-free plants.
- **Indirect Organogenesis** occurs when organ development follows the formation of an unorganized mass of undifferentiated cells called callus. The explant first dedifferentiates into callus tissue, which then redifferentiates to form shoots or roots under specific culture conditions and hormonal treatments. This method provides a powerful platform for genetic transformation and somaclonal variation studies but may introduce more genetic variability among regenerated plants.

Hardening

Both approaches involve phases of explant selection, culture initiation, induction of organogenesis via hormonal manipulation, and regeneration of complete plantlets, with their choice depending on the plant species, explant type, and experimental goals. Organogenesis is widely used in fundamental research, mass propagation, genetic improvement, and conservation of plant species. Hardening is a critical phase in plant tissue culture that involves gradually acclimating in vitro grown plants to ex vitro (natural) environmental conditions to enhance their survival and growth after transplantation. It is generally divided into two stages: primary and secondary hardening.

- **Primary Hardening:** This is the initial acclimatization stage where delicate, tissue culture-derived plantlets are gently transitioned from aseptic culture vessels to a controlled environment such as a greenhouse or a growth chamber. After removing plantlets from the nutrient media, they are carefully washed to remove any agar residue. The plantlets are then transferred into small pots or trays filled with a sterile, well-drained substrate like a mixture of soil, sand, and cocopeat or vermiculite. During primary hardening, environmental conditions such as humidity are kept high (often using plastic covers or misting systems), while light intensity and temperature are gradually adjusted to mimic natural conditions. This stage typically lasts 4-8 weeks and helps plants develop functional stomata, thicker cuticles, and stronger root systems essential for water uptake and stress tolerance.

- **Secondary Hardening:** Following primary hardening, plants are moved to less controlled environments such as net houses with reduced humidity and natural light conditions to further strengthen their physiological and morphological traits. In this stage, plantlets are grown in larger containers or polybags containing potting mixtures, promoting root expansion and shoot vigor. Gradual exposure to ambient humidity, temperature fluctuations, and direct sunlight stimulates adaptive responses, preparing plants for field conditions. This phase may last another 4-8 weeks, depending on species and climate. Successful secondary hardening results in robust plantlets that can be transplanted to farmer fields or natural environments with higher survival rates.
- Both hardening phases involve careful monitoring of watering, shading, and pest protection to avoid stress and losses. This gradual acclimatization process bridges the gap between the controlled in vitro environment and the harsher external conditions, ensuring the efficient establishment and growth of micropropagated plants in the field.

Transplantation

Field transplantation is the crucial final step in plant tissue culture, where acclimatized and hardened micropropagated plantlets are transferred from controlled environments (greenhouse or hardening chambers) to open field conditions for normal growth and development.

The methodology involves the following key practices:

- **Preparation of Plantlets:** Plantlets that have undergone primary and secondary hardening are selected for field transfer. They should have well-developed roots, leaves with functional stomata, and sturdy stems. Excess moisture on roots is gently removed.
- **Site Preparation:** The field or nursery site is prepared by loosening soil, removing weeds and debris, and ensuring proper drainage. Sometimes a nursery bed or raised beds with well-drained soil and organic matter are preferred for initial planting.

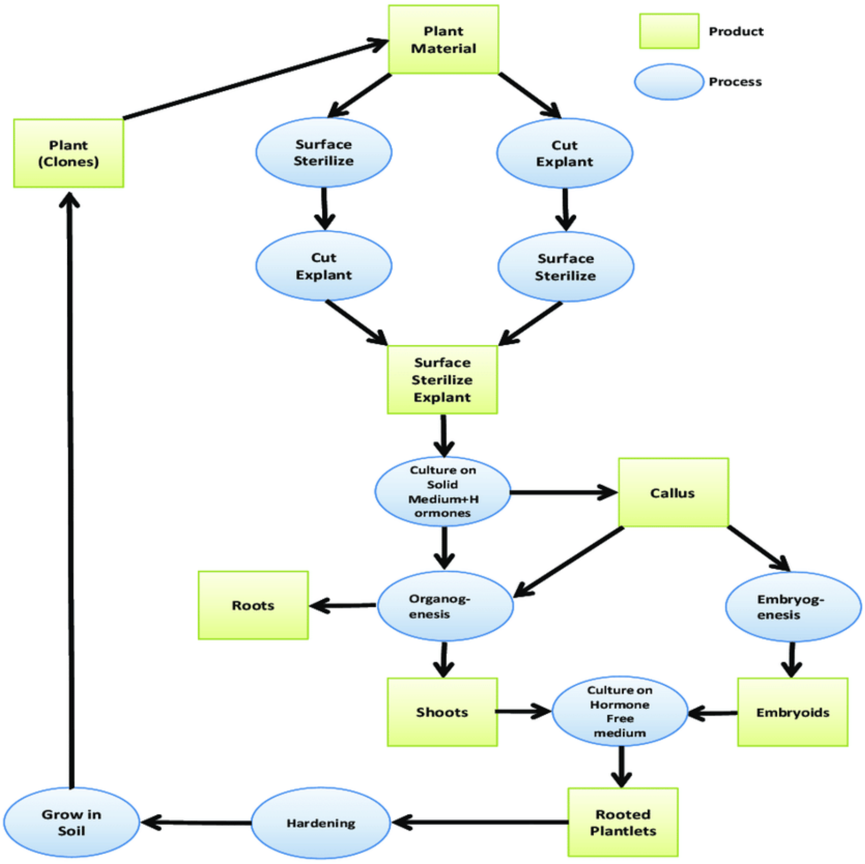

Figure 1. Basic workflow of stages of plant tissue culture:

- **Planting Technique:** Plantlets are transplanted manually or mechanically into the field at recommended spacing suitable for the species, typically planting the root zone below soil surface to ensure good soil contact and support. Care is taken to avoid root damage.
- **Post-Transplant Care:** Immediately after planting, plants are watered thoroughly to settle soil around roots and reduce transplant shock. Shade nets or mulching may be used initially to reduce stress from direct sunlight and evaporation. Regular monitoring for pests, diseases, and nutrient deficiencies is maintained.
- **Irrigation and Nutrient Management:** Adequate watering schedules are followed, adjusting frequency based on climate and soil moisture. Application of balanced fertilizers supports establishment and vigorous growth.
- **Monitoring and Maintenance:** Plants are regularly checked for growth performance and signs of stress. Weeding, pest/disease control, and supplementary nutrition are applied as needed.

Successful field transplantation ensures the conversion of in vitro plantlets into healthy, field-grown plants capable of producing desired yields. This step bridges controlled micropropagation to practical agricultural or horticultural production and requires careful handling to maximize survival and productivity.

Applications of PTC

Plant tissue culture plays a vital role across agriculture, horticulture, and forestry by enabling rapid, disease-free, and uniform plant propagation, genetic improvement, and conservation.

In Agriculture

- Rapid mass multiplication of elite and disease-free crop varieties ensures high yield and quality production.
- Tissue culture aids genetic enhancement by developing crops with improved resistance to pests, diseases, and abiotic stresses like salinity and drought.
- It supports conservation of valuable germplasm and endangered species, preserving biodiversity.
- Enables faster breeding cycles and introduction of novel traits through genetic engineering and somaclonal variation.
- Helps overcome seed dormancy and ensures off-season production for consistent supply.

In Horticulture

- Micropropagation of ornamental and fruit plants provides uniform, high-quality planting material.
- Accelerates propagation of rare and valuable horticultural species.
- Tissue culture techniques assist in producing pathogen-free planting stock, improving overall plant health.
- Facilitates hybridization and breeding of new cultivars with desired traits like flower color and shelf life.

In Forestry

- Tissue culture allows cloning and rapid multiplication of superior tree genotypes and endangered forest species.
- Supports reforestation and afforestation efforts by providing uniform, disease-free seedlings.
- Enables genetic improvement of timber and pulpwood trees for better growth, wood quality, and stress tolerance.

- Assists in conservation of rare and endangered tree species through ex situ germplasm preservation.

Table 4. Common contaminations observed during micropropagation

Type of Contamination	Description	Sources and Examples
Bacterial Contamination	Rapidly growing bacteria cloud the medium, inhibit tissue growth, and may cause tissue death	From explants, human handling, contaminated tools, water
Fungal (Mold and Yeast)	Visible fuzzy mycelium or yeast growth makes the culture medium cloudy and unhealthy; spreads fast in humid conditions	Airborne spores, contaminated instruments, media
Viral Contamination	Harder to detect, viruses cause abnormal growth, stunted development, and often need molecular diagnosis to identify	Infected explants or systemic infection in source plants
Mycoplasma Contamination	Small bacteria-like organisms lacking cell walls, difficult to detect, causing slow culture decline and genetic issues	Often overlooked contaminants, may enter via explants/tools
Chemical Contamination	Toxic chemical residues or incorrect media preparation cause poor growth or tissue necrosis	Residues on glassware, incorrect media formulation
Environmental Contaminants	Dust, spores, or microbes introduced from lab air, surfaces, water, or reagents due to poor aseptic handling or filtration	Airborne particles, contaminated water, improper sterilization

Relevance of plant tissue culture in Agroforestry

PTC plays a pivotal role in strengthening agroforestry systems by enabling rapid, large-scale, and year-round production of elite planting materials. Agroforestry species often exhibit long generation cycles, poor seed viability, and high genetic variability, which limit uniform and quality planting material production through conventional methods. PTC overcomes these challenges by providing clonal propagation of superior genotypes with desirable traits such as fast growth, high biomass yield, disease resistance, and stress tolerance. Through micropropagation, tissue culture ensures the conservation and multiplication of rare, endangered, or recalcitrant tree species, supporting biodiversity and ecosystem restoration. Somatic embryogenesis and in vitro rooting facilitate regeneration of difficult-to-propagate species like *Dalbergia sissoo*, *Tectona grandis*, *Bamboo spp.*, and *Populus spp.*. Moreover, cryopreservation and in vitro gene banks aid long-term germplasm conservation, ensuring genetic resources for future breeding programs. By ensuring uniform, disease-free, and high-performing QPM directly enhances farm productivity, carbon sequestration, and livelihood opportunities. Thus, PTC serves as a critical biotechnological tool in achieving climate-smart, sustainable, and resource-efficient agroforestry systems.

Table 5. Common agroforestry tree species are propagated using PTC technology

Tree Species	Main Uses	Technique	Key Features
Eucalyptus citriodora, E. camaldulensis	Timber, oil, fuelwood	Micropropagation/ meristem culture	Rapid multiplication; virus-free
Tectona grandis	Timber	Micropropagation	High-quality clonal production
Casuarina spp.	Timber, fuelwood, windbreaks	Micropropagation	Uniform establishment
Ailanthus excelsa	Timber, fodder, pulp	Micropropagation	Drought tolerant, fast growing
Melia dubia	Timber, biomass	Micropropagation	Fast-growing, widely adapted
Santalum album	Timber, oil	Micropropagation	Conservation & quality enhancement
Grevillea robusta	Timber, shade, windbreaks	Micropropagation	Adapted to tropical climates

Leucaena leucocephala	Fodder, fuelwood, soil improvement	Micropropagation	Nitrogen fixing, fast growth
Gliricidia sepium	Fodder, fuel, green manure	Micropropagation	Soil enhancer, multipurpose
Gmelina arborea	Timber, pulp	Micropropagation	Quick growth, high-quality wood
Dalbergia sissoo	Timber, pulp	Micropropagation	Quick growth, high-quality wood
Bamboo spp.	Pulp	Micropropagation	Quick growth, high-quality wood
Populus	Timber, pulp	Micropropagation	Quick growth, high-quality wood

Major challenges in plant tissue culture

- **Contamination:** Microbial contamination by bacteria, fungi, and yeast is a persistent and significant issue that can cause culture loss, reduced growth, and experimental failure. Strict aseptic technique, proper sterilization, and use of antimicrobial agents are essential to manage contamination.
- **High Cost:** The setup and maintenance of PTC labs are expensive due to the cost of culture media components (gelling agents, growth regulators, carbon sources), sterile equipment, energy, and skilled labor. This limits accessibility and scale especially in developing countries.
- **Hyperhydricity (Vitrification):** A physiological disorder characterized by excessive water content, translucent tissue, and poor structural integrity that lowers survival rates after transplantation. It can be caused by high humidity, inappropriate media composition, or prolonged culture.
- **Phenolic Browning:** Oxidation of phenolic compounds exuded by explants leads to tissue browning and toxicity, inhibiting regeneration. Use of antioxidants and frequent subculturing can reduce this problem.
- **Somaclonal Variation:** Genetic instability and variation in plants regenerated through tissue culture, especially after multiple subcultures or callus phases, which can affect uniformity and desired traits.

- **Recalcitrance of Species/Explant:** Some plant species or explant types are difficult to culture because of poor response to regeneration or rooting, requiring protocol optimization.
- **Labor Intensive and Time-Consuming:** The tissue culture process involves multiple meticulous steps demanding skilled personnel and substantial time investment.
- **Acclimatization and Hardening Losses:** High mortality during transfer of plants from in vitro to ex vitro conditions due to stress from environmental changes.
- **Limited Infrastructure and Skilled Workforce:** Many regions face shortages of trained staff, reliable utilities (electricity, water), and adequate lab infrastructure needed for consistent PTC operation.

Addressing these challenges requires improved protocols, cost-effective technologies, skilled training, integrated contamination management, and infrastructure development to fully harness tissue culture potentials in agriculture and horticulture.

Future perspectives

- Increasing demand for disease-free, genetically uniform, and high-yielding plant varieties.
- Advancements in automation and robotic systems to enhance large-scale propagation efficiency and reduce labor costs.
- Integration of Artificial Intelligence (AI) for optimizing culture conditions, predicting plant development, and improving reproducibility.
- Application of cutting-edge gene editing technologies (e.g., CRISPR-Cas9) combined with tissue culture for precise crop improvement.
- Development of bioreactor technologies for scalable and controlled in vitro plant production.
- Expansion into controlled-environment agriculture and vertical farming, enabling sustainable year-round production.
- Tissue culture as a key tool for conservation of endangered species and biodiversity preservation.
- Innovations in cost-effective media formulations and eco-friendly protocols to reduce expenses and environmental impact.
- Synergistic use with molecular breeding, marker-assisted selection, and high-throughput phenotyping for precision breeding.
- Enhanced role in global food security by enabling rapid multiplication and distribution of stress-tolerant, climate-resilient crops.

- Collaborative research and standardization to overcome current technical challenges and scale adoption worldwide.
- Potential integration with synthetic biology and omics technologies to deeply understand and engineer plant developmental pathways.

These emerging trends position plant tissue culture as a vital technology for sustainable agriculture, environmental conservation, and biotechnology innovation in the coming decades.

A Climate-Resilient Modern Horticulture-Based Agroforestry System for Nutrition and Livelihood Security

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Abstract

Ensuring nutrition and livelihood security under the challenges of climate change, land degradation, and resource scarcity remains a major concern, particularly in developing countries. Horticulture-based agroforestry systems offer a promising, climate-resilient solution by integrating trees, fruit crops, fodder, and intercrops within a single production unit. This modern climate-resilient horticulture-based agroforestry model is designed to enhance farm income, nutritional diversity, ecosystem services, and climate adaptability. The model consists of three distinct components: (i) boundary plantation of multipurpose tree species combined with Bajra–Napier hybrid grass for fodder and biomass production, (ii) an inner layer of perennial fruit crops rich in nutrients and bioactive compounds, and (iii) an intermediate layer of compatible intercrops such as cereals, pulses, vegetables, spices, or medicinal plants. The system ensures year-round production, reduces the risk of total crop failure, improves microclimatic conditions, enhances soil health, and contributes to carbon sequestration. By mimicking natural forest structure while remaining farmer-friendly and economically viable, this model demonstrates strong potential for sustainable agriculture, climate change adaptation, and improved rural livelihoods. Widespread adoption of such climate-resilient agroforestry systems can significantly contribute to long-term nutrition security, income stability, and environmental sustainability.

Keywords: Climate-resilient; Horticulture-based agroforestry; Nutrition security; Livelihood security; Boundary plantation; Fruit-based farming systems; Sustainable farming; Ecosystem services; Carbon sequestration

Introduction

Nutritional security is achieved throughout a healthy lifespan only when individuals have consistent access to adequate, safe, and nutritious food. It's not just about calorie intake, but also about eating a balanced diet rich in essential nutrients. Livelihood security requires individuals and families to have sustainable access to income-generating opportunities to meet their basic needs and protect themselves from risks.

Despite numerous challenges, such as population growth and climate change, researchers and governments are making every effort to improve nutrition and livelihood security.

Globally, in 2022, there were 37 million overweight children, 45 million wasted children, and 148.1 million stunted children under five years of age. Over the past ten years, stunting has been gradually decreasing; in 2022, 148.1 million children under five years of age worldwide were affected, or 22.3 percent. Nearly all of the affected youth lived in Asia (52% of the global share) and Africa (43% of the global share). It is estimated that 6.8% of children under five years of age were wasted in 2022, of which 13.6 million (2.1%) were severely wasted. More than 75% of children with severe wasting live in Asia, while 22% live in Africa. Overweight has increased in prevalence practically everywhere over the past 20 years.

Various challenges, such as climate change, soil erosion, land shrinkage, water scarcity, and biotic and abiotic stresses, will impact crop production and productivity, resulting in reduced availability of balanced diets for the growing population. Under these circumstances, horticulture-based agroforestry systems will play a crucial role in protecting nutrition and environmental security. The National Family Health Survey (NFHS-5) of 2019–2021 showed that the prevalence of malnutrition in India varied by age and type:

Modern climate-resilient horticulture-based agroforestry model

To curb nutritional and livelihood security, this modern climate-resilient horticulture-based agroforestry model can play a vital role. This model is a unique, remunerative, farmer-friendly, and climate-resilient model and can be best suited for present and future scenarios

Component A or Outer layer: In this portion, the tree component is planted on all four sides of the field boundary of the field at a particular spacing recommended for particular tree species. This layer is based on the theme of Har-Med Par Med to encourage tree plantation on farmland, along with crops/ cropping systems to help the farmers get additional income and make their farming systems more climate resilient and adaptive. The suitable tree crops for this layer are malabar neem, mahogany, teak, eucalypts, gamhar, poplar, and palash.

The vacant interspace between the trees should be used for planting the Bajra Napier Hybrid grass. The perennial Bajra-Napier hybrid grass, sometimes referred to as elephant grass or king's grass, is a cross between the two types of grass. Because of its high biomass, it has the potential to be a biofuel crop. Along with being a very tasty and succulent herb, it also feeds livestock. With its broad, velvety leaves and two to three-year field life, this grass is a favorite among dairy farmers. It is tolerant of mild drought and hardy to harsh conditions. 150–200 tons of green feed can be produced per hectare from the grass. Up to 1100 quintals can be produced per acre by some types, such as PNB 233. Deep, well-drained loams with a pH between 4.5 and 8.2 and regions with more than 1,000 mm of rainfall are ideal for its growth. Some popular varieties include CO-1, CO-2, CO-3, APBN-1, PBN-83, Yashwant (RBN-9), IGFRI-5, NB-21, NB-37, PBN 233, Suguna, Sampoorna (DHN 6), Supriya, APBN-1, and KKM-1. Besides the fodder, farmers can earn more money from selling the rooted slips of Bajra Napier Hybrid.

Component B or Inner layer:

In this component, perennial fruit crops are preferred and grown at recommended spacing. This crop should be of medium height and selected based on soil and climatic conditions of the particular region. This crop can start fruiting commercially on average 4-5 years after the plantation. The suitable crops of this component are pomegranate, guava, mango, ber, date palm, citrus, apple, peach, pear, aonla, and bael. Since fruit crops are rich in antioxidants, minerals, and other bioactive compounds, this layer will help in increasing the fruit production of the country and thereby nutritional security and livelihood security.

Component C or Intermediate layer:

The crop of this component is planted as an intercrop of the fruit crop present in component B. In this farm, can plan for the traditional agronomic crop (wheat, mustard, pulses) of the region or you can plant vegetables, spices, or medicinal plants to get a higher price. The major criteria for selecting the intercrop in this layer should be that the intercrop height should not be more or equal to the fruit crop selected in component B.

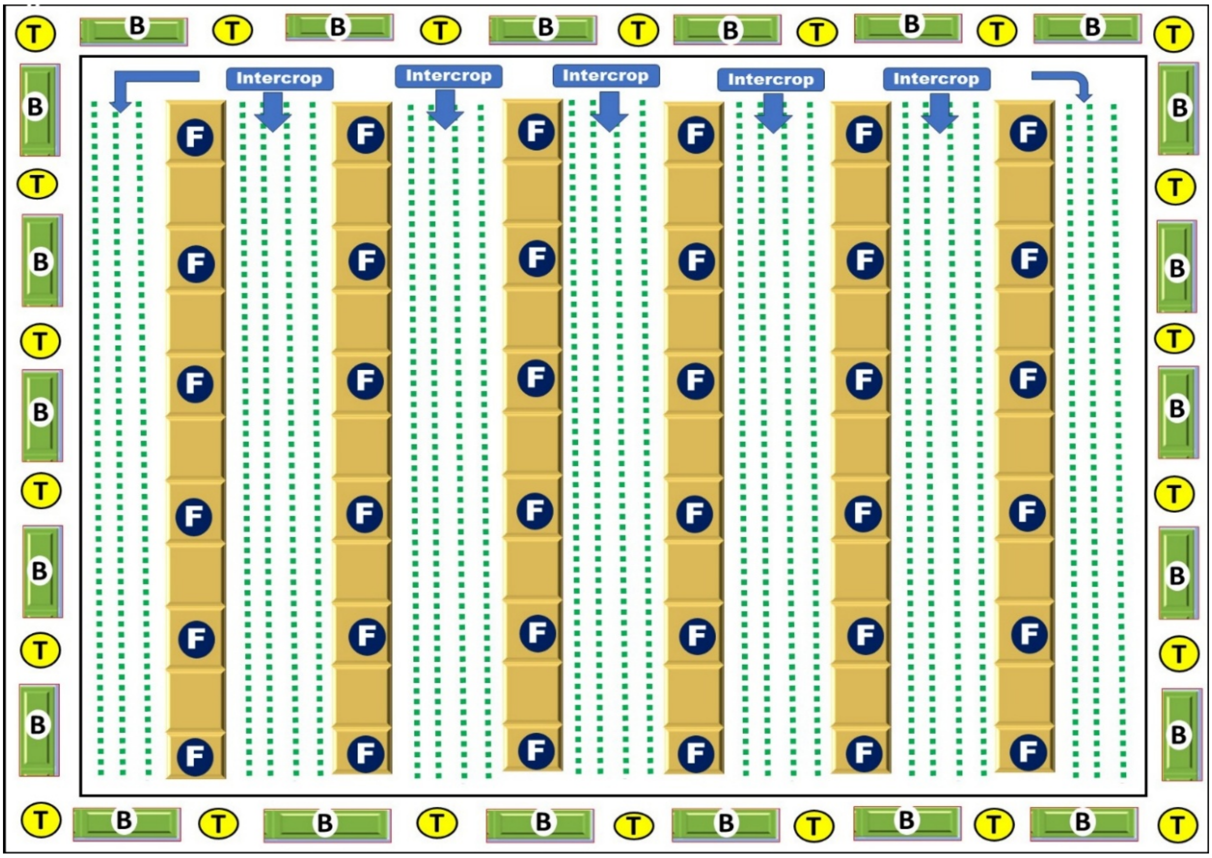

Figure 1. Modern climate-resilient horticulture-based agroforestry model (T: Tree crop, F: Fruit crop, I: Intercrop, B: Bajra Napier Hybrid grass) (Source: Yadav et al., 2025)

Importance and benefits

- This model will provide continuous and remunerative income to the farmers. In this model, the farmer can take a minimum of three crops a year because of a reduction in the incidence of total crop failure, common to single-cropping or monoculture systems.
- This model will act as an excellent example of climate change adaptation.
- Improvement of microclimate, such as lowering of soil surface temperature and reduction of evaporation of soil moisture through a combination of mulching and shading
- This boundary plantation in the model acts as a windbreak and will reduce the harmful effects of a heat wave and cold wave.
- This model will provide continuous green fodder (Bajara Napier Hybrid) to animals throughout the year.
- This model will Helps in maintaining plant biodiversity
- This model will provide different ecosystem service

- In case of crop losses due to adverse climatic conditions, the compensation can be covered under two crops taken during the year.
- This model has great potential for carbon sequestration.
- This model will provide the opportunity to mimic a natural forest in farmland with high complementary economic and environmental benefits.
- Increment in soil nutrients through the addition and decomposition of litter-fall.
- Improvement of soil structure through the constant addition of organic matter from decomposed litter
- This model will provide food, fuel wood, fodder, fertilizer, and timber.
- Improvement in nutrition and health due to increased quality and diversity of food outputs.
- Improvement in rural living standards from sustained employment and incomes.

Important intercultural operations

Selection of plant species and the variety:

Choosing native tree species (On-field bunds) and fruit species (Inside the field) that are well-suited to the local climate and soil conditions, often with additional benefits like providing shade, fixing nitrogen, or producing edible fruits. Improved variety (forest and fruit plants) should be selected, and true-to-type planting material should be planted in the field to get a better return from the field.

Spacing:

Plant the boundary trees and fruit crop inside the field at a particular and recommended spacing for ease in different intercultural operations

Intercrop: The intercrop between the fruit crops should be selected wisely and should not have adverse effects on each other**.** The farmers can select traditional region-specific agronomic intercrop or vegetable crops for quick and higher returns.

Crop rotation: Since the boundary and fruit crops are perennial components in this model, Therefore, one should go for crop rotation among the intercrops grown in the field. This will help in optimizing the nutrient cycling and minimizing pest and disease issues.

Training: Training should be done from time to time for both tree components on field bunds and fruit trees grown inside the field. This is mainly done to maintain desired canopy cover and optimize crop production. In training, removing the side branches from time to time to get a clean and clear bole is essential in tree components, whereas in the case of a fruit tree, it depends on the type of fruit crop selected.

Pruning techniques:

Among the pruning methods, maintenance pruning is highly preferred by removing the diseased, decayed, and dry branches, diverting the sap flow to the growing parts.

Thinning:

In the case of Bajra Napier hybrid grass, one should cut it timely and thinning the slips of the grass should be done timely. Thinning should also be done when branches become crowded in the fruit crops which is grown inside the field

Integrate Pest and disease management:

The selection of trees, fruit, and intercrops should be in such a way that one plant species' pests and diseases should not affect each other. Timely precautionary measures should be taken to control pests and diseases before they become serious

Hygiene maintenance

Precautions should be taken to ensure the care of clean cleanliness of the field to avoid the spread of pests and diseases from infected parts. The infected pruned material or decayed fruit or produce should not be kept in the field to avoid the spread of infection.

Conclusion

The above-mentioned modern climate-resilient horticulture-based agroforestry model is in need of the present and future for not only better income but also for nutritional and livelihood security. Besides this, this model will protect Mother Earth from various climate change-induced stresses. Therefore, more awareness programmes should be conducted to highlight the importance of the climate-resilient horticulture-based agroforestry model. So that farmers can change their mindset and adopt this type of model more and more to enhance their socio-economic status.

Abiotic stress management of crops under an agroforestry system in arid and semi-arid regions

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Abstract

Global warming is a greatest threat worldwide due to its extreme weather events such as extreme drought, heatwaves, flood, sea-level rise *etc*. Due to sessile in nature, crop plants have to develop certain strategies to cope with various abiotic stress like drought, heat, combined heat and drought, salinity, high light, cold stress (chilling/freezing) *etc*. Agroforestry (integration of trees along with crops and livestock components in the same piece of land) seems to be a viable option to mitigate the negative effect of abiotic stress by moderating microclimate variables, thus providing conducive environment for proper functioning of the photosynthetic systems and other key soil biological activities to boost the crop yield. Moreover, it is also noteworthy to mention that as light is utmost requirement to maximize the crop growth and productivity, the adoption of agroforestry systems can impose low light condition depending upon the canopy structure of trees *i.e.* shade to the underground cultivated crops, further jeopardizing the crop productivity. Thus, proper planting geometry and its management is important to maintain the crop yield *at par* with control (open field) condition. However, canopy management and pruning, net shading, mulching and biochar application can also contribute to stress tolerance in various agroforestry systems. In this article, several strategies for drought and heat stress management of crop under agroforestry system has been discussed.

Keywords: Agroforestry; Drought stress; Heat stress; Management

Background

As per the 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2021), it is forecasted that the global warming level may be crossed to 1.5°C in the following decades (Arias et al., 2021). Abiotic stress significantly impacts the reproductive development of different crops, ultimately resulting in lower economic yield. Furthermore, global food security is becoming increasingly concerned due to this rising global temperature and frequent strong heat waves (Fontana et al., 2015; Mueller et al., 2015). High temperature adversely affects the yield potential of crops by negatively affecting their metabolic pathway and thereby, yield losses may reach up to 70% under heat stress during grain filling conditions (Wollenweber et al., 2003).

Among the various abiotic stresses, the effect of drought and high-temperature stress on grain yield is complex, which includes nutrient assimilation and their mobilisation to various reproductive parts, the accumulation of stem reserves (mostly water-soluble carbohydrates), gametogenesis, fertilization, embryogenesis, and endosperm development and seed development as well (Sehgal et al., 2018). Furthermore, the combined action of heat and drought stress is the major concern nowadays, limiting crop yield greatly as compared to individual drought and heat stress. In these scenarios, adoption of agroforestry (integration of woody perennials with crops along with livestock) seems to be an effective strategy to mitigate the negative effects of abiotic stress like drought, heat and combined heat & drought stress.

Agroforestry manages abiotic stress in arid and semi-arid regions by creating a more favorable microclimate, improving soil health, and enhancing water management. Trees reduce wind speed, lower extreme temperatures, and increase soil moisture through shade and bio-drainage, while deep-rooted shrubs bring water from lower soil layers to the surface for crop use. This strategy mitigates common stresses like drought, heat, and combined stress and thereby increasing crop resilience and productivity. Moreover, the type of abiotic stress encounters by the crop plants is given in Fig.1.

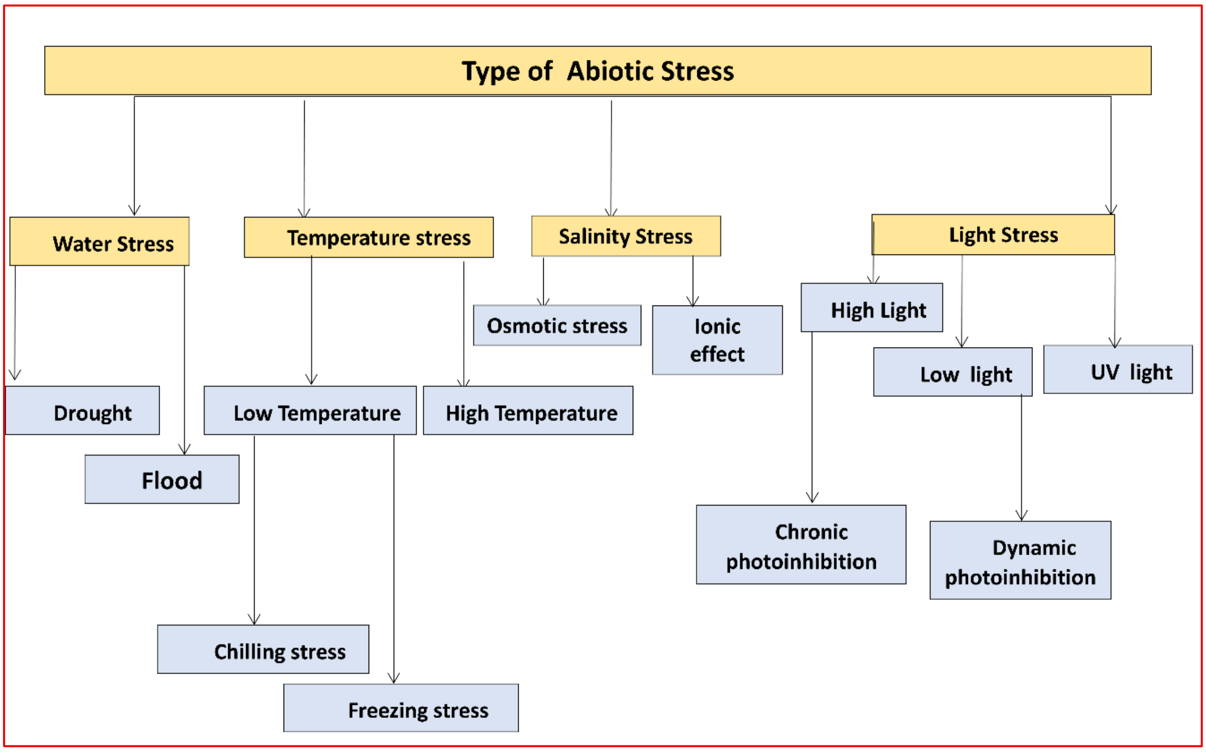

Figure 1. Type of abiotic stress encountered by plants

Agroforestry and Drought Stress Management

The absence of rainfall over a period of time is generally called as drought stress. Under drought stress, plants are unable to get sufficient water for their key physiological activities, resulting in dysfunction of the source-sink activities, which hampers assimilate partitioning, a key factor in boosting crop yield. Drought stress also resulted in poor pollination, early flowering, leaf senescence, protein denaturation, which ultimately resulted in poor growth and yield. Plants generally respond to drought stress by three mechanisms (1) drought escape, (2) drought avoidance, (3) drought tolerance (Fig.2)

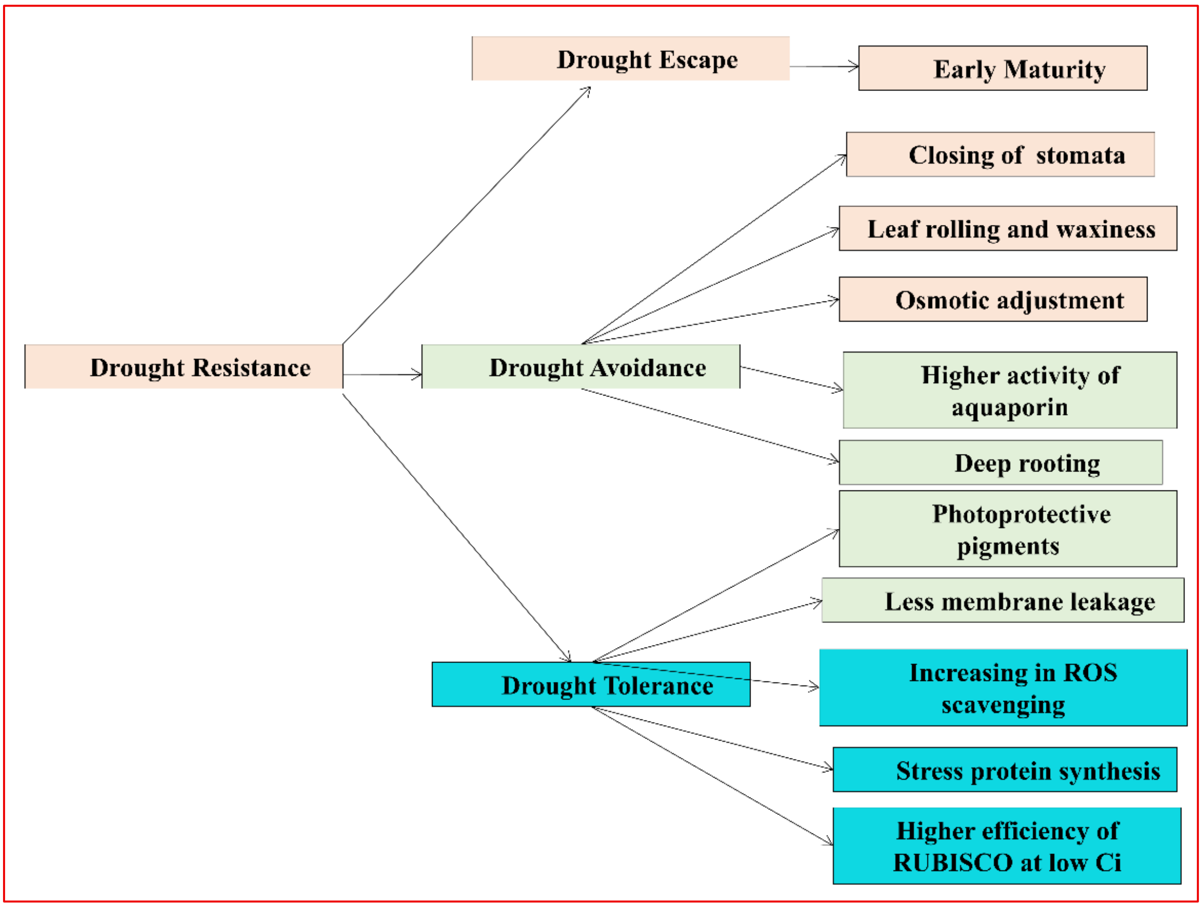

Figure 2. Drought resistance mechanisms in plants

Drought escape

It is the ability of plants to shorten their growth period to complete its life cycle before drought stress encounters. This is achieved by adjusting its development, such as early flowering and other phenological adjustment.

Drought avoidance

It is the ability of the plants to maintain the high tissue water content by reducing the water loss through stomatal closing mechanism as well as by increasing the water uptake through extensive root systems.

Drought tolerance

It is the ability of the plants to tolerate or endure drought stress even at low tissue water potential through osmotic adjustment, compatible solute, antioxidant systems and increase in cell wall plasticity. However, agroforestry system can minimize the effect of drought stress broadly by two ways (A) microclimate moderation, (B) moisture availability to root systems.

a. Microclimate moderation

Trees lessen the wind speed, which reduces soil erosion and water loss from evaporation. They also lower maximum temperatures and provide shade, buffering crops from high heat and intense radiation, which also intensify the drought stress. Introduction of woody perennial tree species in cropping system can modulate radiation flux (low fluence rate), air temperature and saturation deficit (Rao et al., 2007). Microclimate variable includes solar radiation interception, leaf canopy temperature, relative humidity and higher soil moisture content (Fig.3). Certainly, aboveground microclimate moderation has direct effect on soil microclimate regardless of type of agroforestry systems (van Noordwijk et al., 2014; Karki and Goodman, 2015). Microclimatic moderation has a major impact on crop performance as it affects growth, development and yield in various crop species (Slingo *et al*., 2005). It was observed that different genotypes of *Dalbergia sissoo* moderate the microclimate variables (air temperature, canopy temperature, canopy temperature depression, relative humidity) differently on understory crop, cowpea (Alam et al., 2018), indicating genetic variation in trees species for moderating microclimate variables. Study reported that *Gmelina arborea*-based agroforestry system and *Alnus nepalensis*-based agroforestry system modified the leaf chlorophyll content, stomatal conductance, stomatal size and stomatal frequency in understory crops (Rangappa et al., 2025), emphasizing the role of agroforestry in moderating/modulating the key yield-contributing traits in plants. Greater microclimate moderation was recorded nearer to the trees row in alley cropping systems (Jacobs *et al*., 2022), which clearly indicates the role of agroforestry in providing conducive micro-environment near the understory crop for better crop yield and productivity under drought stress.

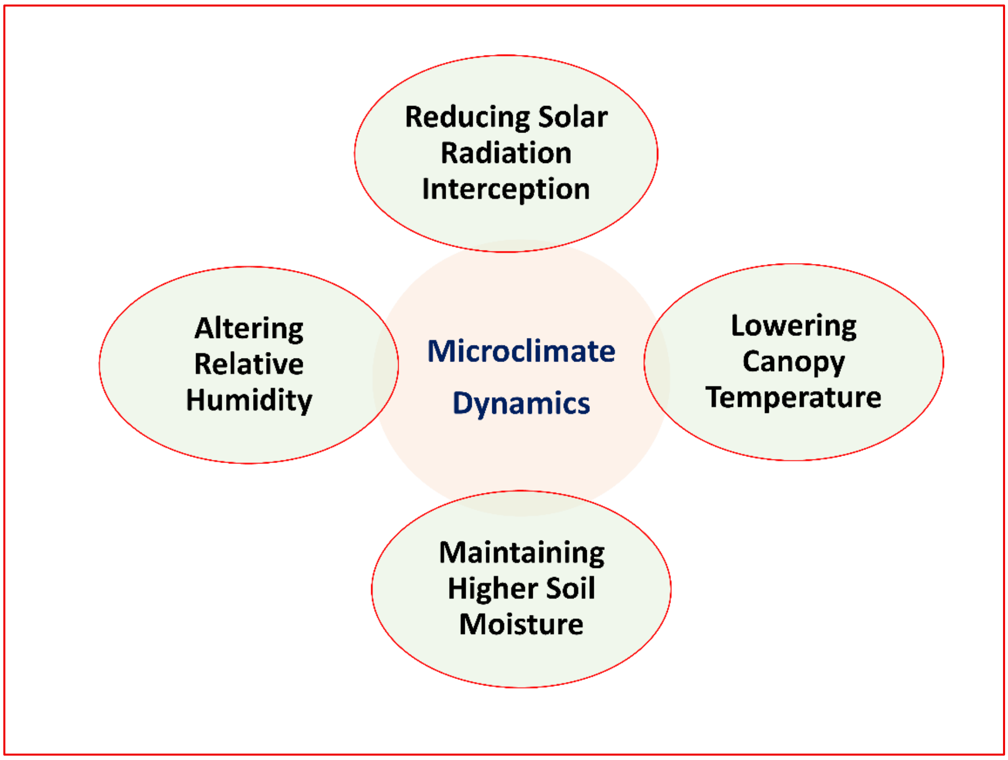

Figure 3. Microclimate moderation under agroforestry systems

b. Moisture availability to root systems

Tree roots can absorb water through a process called as "hydraulic lift", where water moves passively from deeper and wetter layers to shallower and dryer soil layers along soil water potential gradient through tree roots. It is also noteworthy to mention that tree's canopy affects evaporative demand. Furthermore, Lovell et al. (2018) reported that potential evapotranspiration was reduced by 70% under agroforestry systems. Increased infiltration rates and hydraulic lift combined with decreased atmospheric evaporative demand would lead lead to greater moisture levels in the topmost soil layer, which can available to the understory crops. It was reported that soil moisture content (SMC) consistently decreased from by 1%–3% with increasing distance from the tree row in a walnut-based alley cropping system in Southern France (Guillot et al., 2019).

Thus, by adopting specific tree-crop combination, drought stress in crops can be minimized by moderating micro-climate variables suitable for efficient photosynthetic systems and by providing available soil water near the rooting zones of crops for proper functioning of the key vital mineral nutrient transporters in plants. Furthermore, application of bioregulators can also improve the drought tolerance in crops under agroforestry systems. However, very scanty information is available regarding role of plant hormones in mitigating drought stress of crops under various agroforestry systems. Some of the potentials role of plant hormones in mitigating drought stress in crop plants adopted under agroforestry systems is given in Table 1.

Table 1. Plant Hormones and Drought Tolerance

Plant	Phytohormone	Mechanism	Reference
Soybean	ABA	Proline and antioxidative enzyme activity increased. Reduced stomatal size	Li et al., 2013
Maize	ABA	Increased ABA accumulation and drought tolerance	Lu et al., 2013
Barley	Cytokinins	Drought avoidance mechanism	Pospíšilová et al., 2026
Chickpea	Thiourea Benzyladenine Thidiazuron	Inducing the expression of RbcL and photorespiratory genes	Vineeth et al., 2016
Chickpea	Paclobutrazol	Enhanced ABA level and chlorophyll biosynthesis	Soumya et al., 2017
Soybean	6-benzyl adenine	Enhanced bud formation, shoot proliferation	Mangena, 2022
Spring wheat	Gibberellic acid	Enhanced ascorbate level, decrease in reduced/oxidized glutathione (GSH/GSSG) ratio	Moumita et al., 2019
Mung bean	Indole-3-butyric acid	Enhanced antioxidant systems	Li et al., 2018
French bean	Methyl Jasmonate and Salicylic Acid	Enhanced catalase, peroxidase, superoxide dismutase, glutathione peroxidase, and glutathione-S-transferase, enzymes of the ascorbate–glutathione cycle	Mohi-Ud-Din et al., 2021

Apart from plant hormones, plant use myriad of adaptative mechanisms to cope with low moisture availability including the use of beneficial microorganisms such as plant growth promoting rhizobacteria (PGPR). Inoculation of plant roots with different PGPR species has been revealed to promote drought tolerance through various physiological, biochemical, molecular, nutritional, metabolic, and cellular processes, which include enhanced plant growth and root elongation for water absorption. Therefore, plant colonization by PGPR is an eco-friendly agricultural method to improve plant growth and productivity. The inclusion of PGPR in different agroforestry systems has to be studied critically to decode the differential mechanism of PGPR-induced drought avoidance/drought tolerance mechanism. Potential role of PGPR in mitigating drought stress in plant is given in Table 2.

Table 2. Contributions of plant growth-promoting rhizobacteria (PGPR) to alleviation of drought stress in plants

PGPR strains	Drought-stressed plant	Effects	References
Rhizobium	*Phaseolus vulgaris* L.	Enhanced nutrient content and yield	Yanni et al., 2016
Sphingomonas sp., strain LK11	*Glycine max* L.	Increased ABA, Jasmonic acid, and photosynthetic pigments	Asaf et al., 2017
Pseudomonas putida strain FBKV2	*Zea mays* L.	Enhanced shoot and root growth, decreased stomatal conductance	Vurukonda et al., 2016
Variovorax paradoxus strain 5 C-2	*Pisum sativum* L.	Reduced ethylene concentration, increased nodulation	Belimov et al., 2009
M. mediterraneum strain LILM10	*Cicer arietinum L.*	Increased nodule number and grain yield	Romdhane et al., 2009

Agroforestry and Heat stress management

During full sunny day, head load on a leaf exposed to full sunlight is very high. However, this enormous heat load is dissipated by the emission of long wave radiation, by sensible (i.e., perceptible) heat loss, and by evaporative (or latent) heat loss.

Sensible heat loss: If the temperature of the leaf is higher than the air circumventing around it, the heat is transferred from leaf to air.

Evaporative/latent heat loss: The process of evaporation from leaf surface requires energy. During the process, it withdraws heat from the leaf and cool the surface.

Sensible heat loss and latent heat loss are the important process of regulation of leaf temperature and is ratio is called as Bowen ratio.

$$\textbf{Bowen ratio} = \frac{\textbf{Sensible heat loss}}{\textbf{Evaporative heat loss}}$$

In well water crops, transpiration, hence water evaporation from the leaf is high, thus Bowen ratio is less. However, stomata closing events during drought avoidance response limit the evaporation from leaf, thus Bowen ratio is high. Plants with very high Bowen ratios conserve water but have to endure very high leaf temperatures in order to maintain a sufficient temperature gradient between the leaf and the air. Slow growth is usually correlated with these adaptations Hence; Bowen ratio index has to be critically studied to decipher the temperature regulation of crops under various agroforestry systems.

Tree-based farming systems often exhibit greater evapotranspiration rate as compared to traditional cropping systems (open field). As a result, crops can maintain their key physiological activities through evaporative-cooling mechanism. Therefore, adding trees to the agricultural system i.e. agroforestry systems may diversify it and act as a buffer against the hazards connected with climate unpredictability based on severe temperatures. Thus, diversifying the production system through incorporating the tree component may provide the buffers against risks associated with extreme temperature-based climatic variability (Dobhal et al., 2024). Trees play dual role in mitigating higher air temperature. Firstly, by intercepting solar radiation and preventing from warming the surface beneath the tree canopy and secondly by transforming energy into latent heat flux *via* water transpiration released through leaves' stomata (Rahman et al., 2020). The impact of agroforestry systems on temperature moderation is given in Table 3.

Table 3. Influence of agroforestry on temperature modifications.

Agroforestry systems (AFs)	Regions	Findings	Reference
Poplar-wheat short rotation alley cropping system	Brandenburg State (Germany)	The air temperature was at least 1°C lower during the daytime and at least 1°C higher at night	Kanzler et al. (2019)
Agroforestry systems (AF) vs Full sunlight (FS)	Mediterranean climate of France	1.2°C lower during day time, while 0.15°C during night time Temperature varied differently during spring *vs* winter season.	Gosme et al. (2016)
Poplar-wheat based AFs	India	Atmospheric humidity was directly proportional to within row spacing of trees while air temperature showed the inverse relation	Chauhan and Dhiman, 2007
Silvo-pastoral system	Brazil	Atmospheric temperature was lower in shadowing area than sunny area	Deniz et al. (2019)
Simulated shade	India	Canopy temperature depression (CTD) increase with increased intensity of shade due	Alam et al. (2024)

		to down-regulation for leaf transpiration process under shade	

Factors influencing cooling capacity of tree species

Choice of site- Compared to plantings in narrow pavement squares, the plants in large green squares can more efficiently reduce ground heat absorption and speed up boundary layer cooling (Rahman et al., 2016), highlighting the choosing of sites for adopting agroforestry system can influence the evapotranspiration cooling capacity of trees species.

Tree architecture – Leaf shape, canopy arrangement (horizontal *vs*. vertical arrangements of leaves), canopy density, evapotranspiration diurnal pattern influences the temperatures under tree canopies.

Furthermore, application of bioregulators can also improve the heat tolerance in crops However, very meagre information is available regarding role of plant hormones in mitigating heat stress of crops under various agroforestry systems. Some of the potentials role of plant hormone in mitigating heat stress in crop plants adopted under agroforestry systems is given in Table 4.

Table 4. Plant Hormones and Heat Tolerance

Plant	**Phytohormone**	**Mechanism**	**Reference**
Wheat	Salicylic acid	Enhanced yield-related traits	Lakhran et al., 2021
Wheat	Gibberellic acid Paclobutrazol	Higher antioxidant enzyme activity, membrane stability, and photosynthesis rate. Lower lipid peroxidase activity.	Nagar et al. (2021)
Common Bean	Phytomelatonin	Reduce canopy temperature, increase in pollen viability	Kruthika et al., 2025
Wheat	Salicylic acid	Regulating proline metabolism and ethylene formation	Khan et al., 2013
Wheat	ABA, Cytokinin	Regulating leaf senescence, starch synthesis, antioxidant systems	Sarkar et al., 2021

Though adoption of agroforestry system is a viable option to boost the crop yield by moderating microclimate variables, it can impose shade stress to understory crops, thus lowering the crop yield. Most of the crop plants show shade avoidance syndrome (SAS), an acclimation response for readjusting the growth and development to escape eventual shade condition even at the expense of photosynthesis and defense (Martinez-Garcia and Rodriguez-Concepcion, 2023). Undermining the SAS has the potential to implement shade-tolerant strategies in various crop plants with minimized yield losses, which are generally caused by wasteful carbon investment in non-harvestable stems (Carriedo *et al*., 2016).

Conclusion

Adoption of agroforestry systems can be an advisable option to alleviate the negative effects of abiotic stress in plant as well as for ensuring livelihood security for small and marginal farmers. Future research to understand the SAS in various crops is urgently needed to fine-tune SAS and tailor plant architecture for adapting to shade condition and in agroforestry systems in particular. Different canopy management models can be tested in agroforestry systems to provide unfiltered light to understory crops, thus removing the shade barriers as well as to provide optimum microclimates for proper functioning of the photosynthetic systems. Identification of stress-tolerant genotypes, particularly suitable for different agroforestry systems will also pave the way toward combating harmful effect of climate change events. The possibility of use of plant growth regulator (PGR) in ameliorating harmful effect of stress can be tested and validated under various agroforestry system for further recommendation for farmers.

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Agroforestry for Sustainable Livestock Production under Climate Change Scenario

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Introduction

Livestock sector is an important component of Indian farming system and it contributes significantly to human nutrition, income and employment generation in rural areas. 80% of the rural livelihood in India is nurtured by the agriculture to which contribution of livestock sector is around 25%. Further, livestock sector contributes 4.11% and 25.6% respectively to total GDP and agriculture GDP of India. Moreover, small and marginal farmers in India are completely dependent on livestock for their nutritional requirement; manure input to farms and as well their livelihood. Livestock remains sole source of income to the rural farmers in case of crop failure due to climate vagaries. Thus, improving livestock production is very important for sustaining rural economy in India as India is facing increase in livestock population and decline in their productivity. As per the 20th livestock census, total livestock population in India is about 535.78 million which has increased by 4.43% over previous census of 2012 (table 1). However, average milk productivity of milch animal is very low in India i.e. 2.5 kg/day/animal (indigenous) and 7.2 kg/day/animal (cross breed) compared to 22 kg/day/animal in USA and 28kg/day/animal in UK (Intodia 2017).

Currently we are facing shortage of fodder supply in India and to top it all the ever-rising population of livestock in India is further widening this gap between the demand and supply of fodder. India already faces deficits of 11.40% in green fodder and 23.40% in dry fodder and the growing livestock population is further straining this imbalance. (Roy et al. 2019). If no efforts are going to be taken to bridge this gap, then fodder demand is further projected to reach up to 1012 (green) and 631(dry) million tonnes by 2050 (IGFRI 2015). But mere producing adequate amount of fodder for livestock will not be able to enhance livestock productivity as quality fodder production for livestock needs to be focused upon too as low livestock productivity is 50% attributed to the shortage of fodder (quantity & quality) (Chand and Raju 2008; Gowane et al. 2019). Currently less than 5% of the cultivated area in India is utilized for fodder production which cannot be increased further as food production is prime necessity. Therefore, there is need to integrate fodder production either in already existing farming systems or to find out alternate solutions for quality fodder production to boost rural economy.

Impact of Climate Change on Livestock

Climate change is causing a steady rise in global temperatures, with more frequent and intense heatwaves across the globe. These increasing temperatures, combined with high humidity, directly affect the physiology, behavior, and productivity of farm animals. Among livestock species, dairy cattle are particularly vulnerable to heat stress which alters the hormonal balance, particularly by affecting the secretion of progesterone, luteinizing hormone (LH), and follicle-stimulating hormone (FSH). These hormonal disruptions interfere with the reproductive cycle, leading to poor conception rates, high embryo mortality, and extended calving intervals. Heat stress also has direct impact on milk yield and quality and studies have shown that milk production can decline by 0.7 to 4.0 kg per cow per day under moderate to severe heat stress conditions. Projections suggest that by 2050, milk losses could reach 1.5 to 6.5 kg per cow per day, and by 2070, the decline could further increase to 2.0 to 7.2 kg per cow per day (Ranjitkar et al., 2020). This reduction is attributed to both decreased feed intake and impaired nutrient utilization, as the animal diverts energy towards thermoregulation rather than milk synthesis.

As the climate change is leading to a steady rise in temperature, erratic rainfall, and prolonged droughts is also leading to the negative impact on fodder yield, quality, and grazing resources. Higher temperatures accelerate plant growth and shorten the growing period, resulting in reduced biomass production and lower nutritional value due to decreased protein and energy content in fodder crops and grasses. Irregular rainfall and water scarcity further degrade pastures, causing grasslands to shrink and also reduces grassland production and forage quality. Consequently, livestock farmers face severe shortages of quality green fodder, forcing reliance on poor-quality crop residues and costly feed supplements, which reduces milk yield, animal growth, and reproductive performance.

Thus, to address these challenges, climate-resilient fodder production systems that can ensure round the year nutritious fodder supply, natural shade to the livestock and are more sustainable and adaptive to changing climatic conditions are needs to be promoted across the globe and India. In this regard, fodder-based agroforestry system including *agrisilvipasture*, *silvipasture*, *hortipasture*, and *fodder banks* present effective and sustainable solutions for maintaining livestock productivity at both state and national levels. These systems ensure a continuous and sustainable supply of high-quality fodder throughout the year and can be developed on underutilized lands such as wastelands, degraded grasslands, barren areas, and community lands. Beyond fodder production, they also provide a range of valuable by-products like timber, fuelwood, fruits, fiber, medicinal plants, gums, resins, and tannins, thereby enhancing rural income opportunities. Additionally, fodder-based agroforestry delivers crucial ecosystem services, including soil enrichment, carbon sequestration, climate moderation, and biodiversity conservation. Altogether, these systems contribute significantly to the food, fodder, nutritional, economic, and environmental security of the nation, making them a vital component of climate-resilient and sustainable livestock production.

Table 1. Livestock population scenario in India

Livestock population (Million)	**19th Livestock Census**	**20th Livestock Census**
Cattle	190.9	192.49
Buffaloes	108.7	109.85
Sheep	65.07	74.26
Goats	135.17	148.88
Pigs	10.29	9.06
Mithun	0.30	0.38
Yaks	0.08	0.06
Horses & ponies	0.63	0.35
Mules	0.2	0.08
Donkeys	0.32	0.12
Camels	0.4	0.25
Total	**512.06**	**535.78**
Change in Total Population (Million)	**+ 23.72 (4.43%)**	

Table 2. Land that can be utilized for fodder production in India

Land types	**Thousand hectares**	**Reference**
Barren and unculturable land	16996	Statistical Year Book India 2018
Permanent pastures & other grazing lands	10258	
Culturable waste land	12469	
Fallow lands other than current fallows	11092	

Agroforestry by ensuring following can act as boon for enhancing fodder and livestock production under climate change scenario

- Enhanced fodder biomass production potential (30 - 40 t/ha green fodder production) leading to reducing gap between demand and fodder supply.
- Round the year quality fodder supply to livestock.
- Fodder trees ensure nutrition and essential mineral supply to livestock.
- Ethno-veterinary trees help in disease and hormonal imbalance management in livestock.
- Agro-forestry systems via providing shade to livestock reduce negative impact of climate change (heat stress) on livestock.
- Agro-forestry systems via sequestrating huge amount of atmospheric carbon dioxide and reducing GHG's emission (enteric methane) from livestock sector helps in mitigating climate change.
- Enhanced milk yield and livestock productivity.
- Agro-forestry systems help in restoration of degraded lands, biodiversity, and soil as well as water conservation.

Agroforestry systems for enhanced fodder and livestock production

a. Silvi-pasture System (SPs)

SPs combine fodder trees/shrubs and fodder grasses/legumes on same unit of land along with livestock for production of quality fodder for livestock. SPs are capable of providing 30 - 40 t/ha green fodder per year and sustain 3-4 ACU (Adult cattle unit) per hectare. Fodder trees selected under SPs are rich in protein (10 - 28%) and minerals; thereby ensure protein and essential mineral supply to livestock. Most importantly, fodder trees grown under SPs ensure green fodder supply during lean period i.e. winter and summer season thus can help in reducing feeding cost during this period. These SPs can be very easily established with very low input on degraded lands, wastelands, village lands and community lands. Further, SPs are also capable of mitigating climate change via as sequestrating huge amount of carbon dioxide in its biomass and soil carbon pools.

Figure 1. ***Acacia nilotica* + *Panicum maximum*** **based Silvipasture system**

ICAR-IGFRI has also developed a SPs, wherein Trees: Mahua (*Madhuca latifolia*), Pakar (*Ficus infectoria*), Shahtoot (*Morus alba*), Desi babool (*Acacia nilotica*); Shrubs: Subabul (*Luecaena leucocephala*), Drumstick (*Moringa oleifera*), Sesbania (*Sesbania aegyptica*); Grasses: *Chrysopogon fulvus, Panicum maximum, Cenchrus ciliaris*; Legumes: *Stylosanthes seabrana* and *Clitoria ternatea* has been integrated for round the year fodder supply to livestock (Kumar et al. 2017; Kumar et al., 2024). Grasses and legume under this SPs provide 64 % of the total system's green fodder from July-December month (for cut and carry) and re-growth from harvested grasses during March to April month that can grazed by livestock. Shrubs under SPs provide around 15% of fodder during February to April month and rest 21 % is supplied by trees from January to June months. Suitable fodder trees, grasses and legumes for establishment of Silvipasture under various agro-climatic zones of India have been presented in table 3.

Table 3. Suitable fodder trees, grasses and legumes for establishment of Silvipasture under various agro-climatic zones of India

Zone	Fodder Trees	Grasses	Legumes
Peninsular India	*Anogeissus latifolia, Callindra spp., Leucaena leucocephala, Hardwickia binata, Acacia niltotica, Seasbania sesban, Anthocephalus cadamba, Ailanthus triphysa*	*Panicum maximum, Brachiaria mutica, Heteropogon contortus, Chrysopogon fulvus, Sporobolus coromandelianus, Themeda cymbaria, Sehima nervosum*	*Clitoria trenatea, Stylosanthes hamata, Stylosnathes seabrana Desmanthus spp., Medicago sativa*
Western semi-arid and arid regions	*Acacia nilotica, Ailanthus excelsa, Azadirachta indica, Acacia catechu, Albizia lebbeck, Bauhinia spp., Leucaena leucocephala, Harwickia binata, Prosopis cineraria, Zizyphus numularia, Ficus infectoria*	*Dicanthium annulatum, Cenchrus ciliaris, Cenchrus setigerius, Lasiurus sindicus, Panicum maximum*	*Clitoria trenatea, Stylosanthes hamata, Stylosnathes seabrana, Macroptilium atropurpureum*
	Azadiracta indica, Acacia nilotica, Madhuca latifolia, Leucaena leucocephala,	*Saccharum spontanum, S. bengalense,*	*Vigna unguiculata,*

Indo-gangetic plains	*Ziziphus spp., Bauhinia purpurea, Dalbergia sissoo, Pithecellobium dulce, Ficus infectoria, Morus alba, Moringa oleifera, Albizia lebbeck, Melia azedarach*	*S. arundinaceum, Pasplaum notatum, Panicum maximum, Impereta cylindrica, Chrysopogon fulvus, Heteropogon contortus*	*Cyamopsis tetragonaloba, Glycine max, Stylosanthes hamata,*
Himalayan region	*Grewia optiva, Bauhinia variegata, Morus alba, Ulmus spp., Albizia spp., Ficus auriculata, Toona ciliata, Celtis australis, Salix spp., Quercus spp. Robinia pseudoacacia, Leucaena leucocephala*	*Paspalum notatum, Chrysopogon fulvus Lolium perenne, Festuca arundinacea, Setaria anceps, Dactylis glomerata, Heteropogon controtus, Chrysopogon montanus, Poa annua, Lolium multiflorum*	*Trifolium alexandrinum, Macroptilium atropurpureum, Macrotyloma axillare Neonotonia wightii Trifolium repenes, Medicago sativa, Trifolium pratense*

Heat Stress and the Beneficial Role of Silvipasture in Livestock Production

Rising temperatures due to climate change are increasingly exposing dairy cattle to heat stress, which significantly disrupts their physiological and reproductive functions. Heat stress alters the hormonal balance, particularly affecting progesterone, luteinizing hormone (LH), and follicle-stimulating hormone (FSH). These hormonal imbalances lead to reduced milk productivity, higher embryo mortality, and lower conception rates. Providing shade has been proven to effectively alleviate heat load by up to 50%, helping to maintain animal comfort and productivity. Shaded cows produce approximately 0.7 kg more milk per day than those kept in direct sunlight and show a significantly higher conception rate (44.4%) compared to 25.3% in unshaded cows. In this context, silvipasture systems which integrate trees, pastures, and livestock—offer a sustainable and climate-resilient solution. Trees within silvipasture systems provide nutritious fodder and natural shade, reducing the adverse effects of heat stress while improving milk yield, reproductive efficiency, and overall animal welfare. Thus, silvipasture represents a holistic approach that not only supports livestock productivity under changing climatic conditions but also enhances ecosystem health and sustainability.

b. Horti-Pasture System (HPS)

The interspaces between fruit and plantation tree crops can be utilized for growing fodder crops and grasses. In India, 6506000 ha area under fruit trees and 3744000 ha under plantation crops is available which can be utilized for the cultivation of fodder grasses and grass legume mixtures. Integration of grasses and other fodder crops under orchards also enhanced fruit quality and yield by 20-25 %. Horti-pasture systems developed by IGFRI have can produce 6.5-12 t dry matter/ha even under rain-fed conditions and sustain 2-3 ACU per hectare. List of suitable grasses and legumes species for integration under fruit trees and plantations crops has been provided in the table 3. Such HPs can be established by integration of high yielding grasses and fodder legumes in fruit orchards across the nation.

Figure 2. *Aonla* + *Cenchrus ciliaris* and Bael + *Cenchrus ciliaris* based Horti-pasture system

c. Agri-silvi-pastoral System (ASPs)

Under ASPs agriculture crops, fodder crops and trees can be integrated along with the livestock which can produce 25 - 45 t/ha green fodder per hectare based on the on-crop species, crop rotations, tree species, tree density and management practices deployed under ASPs. ASPs established integrating *Leucaena leucocephala*, *Gmelina arborea*, *Albizia procera* trees with Guinea grass; cow pea and field pea has been reported to produce 39 - 45 t/ha green fodder (Singh et al. 2008). Such ASPs can be established by integration of high yielding fast growing fodder trees on farmland across the nation.

Fodder trees on farm boundary

Fast growing fodder trees like *Leucaena leucocephala*, *Ficus* spp., *Sesbania spp.*, *Gliricidia sepium*, *Moringa oleifera*, *Zizyphus* spp., *Grewia* spp., *Morus* species, can be grown on farm boundary as a plantation for fodder production. 1-3 t dry fodder per /running km can be easily produced by this system. Perennial multi cut fodder grasses e.g. guinea, bajra napier hybrid can also be grown on farm bunds to produce around 1.75 to 2.50 kg green fodder per meter bund per cut.

Fodder banks

High density plantations of fodder trees, shrubs and legume crops in the form of block can be planted to meet out fodder shortage in lean/dry period via producing high fodder/forage biomass. The species raised under these fodder banks are pruned or pollarded regularly for supplying fodder for livestock. They can easily be raised on village community lands and wastelands and if surplus fodder produced by these fodder banks, then it can be dried and stored for lean period. With the density of 49382 plants per hectare mulberry fodder bank established in the humid tropics of Kerala have been reported to produce 32.56 t ha^{-1} dry fodder by following 12 weeks cutting interval (John et al. 2019). Same way fodder banks can be established in various agro-ecological zones of India for sustaining fodder supply.

Importance of tree fodder for sustaining livestock productivity

- Ensured supply of nutrient and protein rich fodder for livestock.
- Enhanced milk production on supplementing tree fodder.
- Shade provided by trees can reduce heat load of livestock up to 50% and enhance conception rate and milk yield in livestock.
- Tannin rich leaves of tree lead to enhancement in the growth performance as well as yield and reduction in the enteric methane emission in livestock.
- Ensured supply of green fodder during lean period.

Economic benefits of fodder-based agroforestry systems

- Enhanced milk yield in livestock.
- Enhanced livestock productivity.
- Reduced winter-feeding cost.
- Reduced expenditure on mineral supplements.
- Sustaining pasture productivity even under climate change scenario.
- Multiple products (timber, fuel wood, non timber forest products etc.) from trees.
- Enhanced income from farm.

Carbon Sequestration and Greenhouse Gas Mitigation through Agroforestry

Agroforestry systems play a significant role in climate change mitigation by capturing and storing atmospheric carbon dioxide in both biomass and soil. Trees integrated into agricultural and livestock systems act as long-term carbon sinks, accumulating carbon in their trunks, branches, roots, and leaf litter. This process of carbon sequestration effectively helps to offset greenhouse gas (GHG) emissions generated from livestock production, such as methane (CH_4) from enteric fermentation. By incorporating tree-based fodder production systems such as silvipasture and agrisilvipasture systems farmers can enhance overall carbon storage while improving land productivity and environmental quality. Consequently, carbon sequestration in biomass under agroforestry systems provides a natural and sustainable means of balancing GHG emissions from the livestock sector, thereby contributing to low-carbon, climate-resilient agriculture as well as livestock production system.

Importance of Integrating Tannin-Rich Fodders Trees under Agroforestry in Reducing Enteric Methane Emissions

Incorporating tannin-rich tree species within silvipasture and hortipasture systems not only provides high-quality fodder and shade but also contributes to mitigating enteric methane emissions from livestock. Certain tree fodders such as guava (*Psidium guajava*), jamun (*Syzygium cumini*), mulberry (*Morus alba*), and bael (*Aegle marmelos*) contain condensed tannins, which are natural plant compounds known to influence rumen fermentation. When fed to ruminants, these tannins bind with dietary proteins and reduce the activity of methanogenic archaea in the rumen, thereby lowering methane (CH_4) production without adversely affecting feed digestibility or animal performance. Thus, the inclusion of tannin-rich tree fodders in silvipasture and hoprtipasture systems represents an eco-friendly and sustainable strategies to enhance livestock productivity, improve feed quality, and reduce the carbon footprint of animal agriculture and contribute significantly to climate change mitigation and environmental sustainability.

Conclusion

Agroforestry, particularly fodder-based silvipasture systems, is a comprehensive solution for sustaining livestock production under climate change. By integrating trees, pastures, and livestock, these systems provide year-round nutritious fodder, reduce enteric methane emissions, and offer natural shade that protects animals from heat stress, mitigating its negative effects on milk production, reproduction, and overall health. India's vast areas of wastelands, village and community lands, permanent grasslands, pastures, orchards, and plantations can be effectively utilized to establish such systems. In addition to improving fodder availability and livestock productivity, agroforestry delivers multiple economic and ecological benefits, including carbon sequestration, microclimate regulation, and valuable co-products such as timber, fuelwood, fruits, and medicinal resources. By enhancing resilience, sustainability, and climate adaptation, agroforestry emerges as a holistic strategy to protect livestock, reduce greenhouse gas emissions, and maintain productive and healthy animal populations in a warming world.

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Ecosystem services in agroforestry: methods for quantification and valuation

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Introduction

Climate change is intensifying the occurrence of droughts, heat stress, irregular rainfall events, and pest or disease outbreaks—factors that pose severe risks to smallholder's dependent on rainfed agriculture (Yuan et al., 2024). Traditional monoculture agriculture, which lacks biological diversity, is particularly susceptible to these disturbances and often performs poorly under climatic extremes. Projections from FAO (2022) warn that without strong mitigation and adaptation measures, global agricultural production could decline by nearly 10% by the middle of this century. Rising temperatures are especially concerning, as many of the world's major staples are already approaching the limits of their heat tolerance. Wheat, rice, and maize show substantial yield sensitivity during vulnerable stages such as flowering and grain filling, with studies estimating yield reductions of approximately 6% for wheat, 3.2% for rice, and 7.4% for maize for every 1°C increase in mean global temperature (Ram et al., 2024).

In this context, agroforestry offers a resilient land-use alternative. Agroforestry integrates trees with crops and/or livestock within the same management unit, creating productive systems with greater structural and functional diversity. This biological complexity helps buffer farming households against climatic shocks, stabilizes yields, and provides diversified income streams through products such as fruits, fodder, timber, and fuelwood. Moreover, agroforestry contributes meaningfully to climate mitigation by enhancing carbon storage in both above- and below-ground biomass, enabling it to serve simultaneously as an adaptation and mitigation strategy (Arunachalam et al., 2025). Beyond climate regulation, these systems improve soil fertility, enhance biodiversity, support efficient water use, strengthen food security, and contribute to rural livelihoods (Ram et al., 2023).

Agroforestry practices vary widely depending on the local context, including alley cropping, silvopasture, windbreaks, home gardens, and agroforestry parklands, among others. The role of agroforestry in carbon farming is increasingly recognized in climate policies and carbon markets. Initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest DegradatioCn) encourage the adoption of agroforestry practices as part of broader strategies to mitigate climate change. According to the Global Forest Resources Assessment (FAO, 2020), the global area under agroforestry is estimated to be 45.4 million hectares. In India, Arunachalam et al. (2022) reported that agroforestry covers 28.427 million hectares, representing about 8.65% of the country's total geographical area (328.747 million hectares). Recognizing its potential to enhance farm incomes, ecological sustainability, and climate resilience, the Government of India launched the National Agroforestry Policy (NAP) in 2014. The policy is operationalized through the Sub-Mission on Agroforestry (SMAF) and several complementary schemes, supporting large-scale adoption through incentives, institutional support, and streamlined regulations. These initiatives have revitalized interest among farmers, researchers, and development agencies, positioning agroforestry as a central pillar in India's transition toward climate-resilient and sustainable agricultural systems.

Besides, provisioning services, agroforestry offers a number of ecosystem services and environmental benefits to the societies. Therefore, understanding and quantifying ecosystem services in agroforestry is essential for giving benefits to its practitioners. Accurate quantification is essential for establishing credibility, as measurable biophysical and ecological indicators are necessary to demonstrate the extent to which agroforestry enhances soil health, regulates water resources, sequesters carbon, and supports biodiversity. After quantification, valuation of ecosystem is very important. Valuation translates quantifiable services into metrics (monetary or non-monetary) that enable comparison, cost-benefit analysis, incentive design (e.g., payments for ecosystem services, carbon credits) and decision making across competing land-uses (Alam et al., 2014). Alam et al. (2014) present one of the first frameworks for the quantification and economic valuation of agroforestry ecosystem services, using tree-based intercropping systems and detailed biophysical and economic modelling. Finally, the policy dimension is crucial. For agroforestry to be effectively integrated into agricultural, land-use, and climate policies, robust and credible ecosystem service (ES) data must be generated and aligned with monitoring, reporting, and verification (MRV) frameworks, policy incentives, and institutional mechanisms.

Despite the considerable potential of agroforestry, several challenges continue to hinder its effective assessment and large-scale adoption. Agroforestry systems are highly diverse in terms of species composition, tree–crop–livestock interactions, and regional ecological conditions, making it difficult to develop standardized methods for measuring ecosystem services. Additionally, many ecosystem services operate across long spatial and temporal scales—such as soil carbon accumulation, which may require decades—raising critical questions about permanence, additionality, and the appropriate time frame for evaluation. While provisioning services are relatively easy to quantify and assign market values to, regulating, supporting, and cultural services often lack direct market pathways and are more complex to evaluate due to their intangible or non-market nature. However, we tried to cover major ecosystem services generated by agroforestry systems and their quantification and valuation. The major ecosystem services are given below:

Major ecosystem services generated by agroforestry systems

Agroforestry systems provide a broad suite of ecosystem services (ES) that support ecological functioning, agricultural productivity, climate resilience, and socioeconomic well-being (Ram et al., 2023). These services are commonly grouped under four major categories defined by the Millennium Ecosystem Assessment (MEA): Provisioning, Regulating, Supporting, and Cultural services. Agroforestry is unique because it simultaneously enhances all four categories due to the multifunctional role of trees integrated with crops and livestock.

A. Provisioning Services

Provisioning services refer to goods obtained directly from agroforestry systems. These outputs directly contribute to household income, livelihood security, and market diversification.

Timber and Fuelwood: Trees in boundary plantations, woodlots, and alley cropping provide harvestable timber, poles, and firewood. Reduces pressure on natural forests, helping biodiversity and carbon conservation. Common agroforestry species cultivated for timber and fuelwood include *Tectona grandis*, *Swietenia mahagoni*, *Acacia* spp., *Grevillea robusta*, *Dalbergia sissoo*, and *Leucaena leucocephala*.

Fodder and Forage: Many agroforestry tree species serve as valuable sources of high-protein fodder, supporting improved livestock nutrition and productivity. Species such as *Leucaena leucocephala*, *Gliricidia sepium*, *Sesbania* spp., and *Morus alba* provide nutrient-rich leaves that can supplement or partially replace conventional feed.

Food and Nutritional Products: Agroforestry systems play a vital role in enhancing food and nutritional security by providing a diverse range of edible products such as fruits, nuts, vegetables, latex, and nutrient-rich leaves. Common species grown in these systems include mango, jackfruit, moringa, banana, papaya, and cocoa, each contributing unique nutritional and economic benefits. By integrating these species into farming landscapes, agroforestry not only supports subsistence needs but also enhances overall dietary quality and food sovereignty.

Medicinal and Non-Timber Forest Products (NTFPs): Agroforestry systems also contribute significantly through medicinal and non-timber forest products (NTFPs). Many tree species provide bark, leaves, flowers, gums, and resins that are widely used in traditional medicine, cosmetics, and various cultural practices.

Genetic Resources: Agroforestry systems play an important role in conserving genetic resources. Trees and shrubs integrated into farmlands help maintain landraces, wild relatives, and a wide range of genotypes that are essential for future crop and tree improvement programs. These on-farm genetic reservoirs support breeding efforts aimed at enhancing traits such as drought tolerance, pest resistance, and nutritional quality.

b. Regulating Services

Regulating services are among the most important benefits of agroforestry, contributing to climate change mitigation, water regulation, microclimate moderation, and pest control. Major regulating services of the agroforestry systems are given below:

Carbon sequestration and climate regulation: Agroforestry is recognized as one of the most effective land-use practices for atmospheric carbon removal. There are multiple pathways for carbon sequestration in agroforestry systems.

a. Aboveground biomass: trunks, branches, leaves.
b. Belowground biomass: extensive root systems.
c. Soil organic carbon (SOC) through leaf litter, root turnover, and reduced soil disturbance.

Magnitude of sequestration:

- Typical rates: 1.5–8.0 Mg C ha^{-1} $year^{-1}$, depending on species and age.
- Silvopastoral systems often show the highest SOC improvement due to continuous carbon inputs.

Soil conservation and erosion control: Agroforestry systems play a significant role in soil conservation and erosion control. The presence of tree canopies helps intercept rainfall, thereby reducing raindrop impact and minimizing splash erosion on exposed soil surfaces. At the same time, tree roots stabilize the soil by binding aggregates and improving structural integrity, which reduces sediment loss. Studies have shown that alley cropping and similar practices can reduce soil erosion by as much as 70–90%, demonstrating their effectiveness in protecting vulnerable soils. In addition to controlling erosion, agroforestry enhances soil structure, increases water infiltration, decreases surface runoff, and promotes better moisture retention factors that collectively contribute to long-term soil health and sustainable agricultural productivity.

Water regulation & hydrological services

Agroforestry influences hydrological cycles by affecting infiltration, groundwater recharge, and evapotranspiration. Key mechanisms include 1. Root systems improve soil porosity and infiltration. 2. Trees shade understory plants, reducing evaporation and 3. Riparian agroforestry buffers filter sediments and nutrients, improving water quality.

Microclimate regulation

Trees in agroforestry systems play a vital role in moderating microclimatic conditions within agricultural fields. By reducing temperature extremes, increasing relative humidity, and lowering wind speed, they create a more favorable environment for crop growth. Tree canopies also protect understory crops from excessive solar radiation, reducing heat and water stress. These microclimatic benefits are especially important for climate-resilient agriculture, helping crops withstand heatwaves, dry spells, and other climate-related stresses.

Pest and disease regulation

Agroforestry systems strengthen natural biological control by creating habitats that support beneficial predators and parasitoids. The presence of diverse plant species breaks the uniformity of monocultures, reducing the likelihood of severe pest outbreaks. Enhanced biodiversity within these systems fosters ecological balance and promotes sustainable pest regulation. For example, shade-grown coffee demonstrates significantly lower infestations of the coffee berry borer due to improved habitat conditions for natural enemies.

Windbreak and shelterbelt services

Trees functioning as windbreaks provide multiple benefits within agroforestry systems. They reduce wind speed, which in turn minimizes crop lodging and prevents soil desiccation. By creating a more sheltered microenvironment, windbreaks also enhance water-use efficiency and offer protection to livestock from heat stress. In arid and semi-arid regions, these protective effects can lead to significant improvements in crop performance, with windbreaks often contributing to yield increases of 10–20%.

Air Purification

Trees filter particulates, sequester pollutants (SO_2, NO_x), and release oxygen.

c. Supporting Services

Supporting services underpin overall ecosystem functioning and productivity.

Soil fertility enhancement

Agroforestry improves soil fertility through nitrogen fixation (leguminous trees like Gliricidia, Sesbania, Leucaena), leaf litter addition improving SOC and nutrient cycling, Improve CEC and pH moderation. It is reported that agroforestry can increase the soil organic carbon (SOC) over the conventional agriculture.

Nutrient cycling

Deep-rooted trees in agroforestry systems act as effective "nutrient pumps" by absorbing nutrients from deeper soil horizons and returning them to the topsoil through leaf litter and root turnover. This natural recycling process enhances soil fertility, enriches organic matter, and supports healthier crop growth. Estimates suggest that a single tree can contribute an average of about 18 kg of leaf litter per year, significantly improving nutrient availability in the upper soil layer and boosting overall crop productivity (Ram et al., 2017).

Biodiversity Enhancement

By integrating trees, crops, and understory vegetation, these systems support a rich diversity of plant species and foster thriving soil microbial communities essential for nutrient cycling and soil health. They also provide habitats and food resources for a wide range of birds, pollinators, and beneficial insects, thereby strengthening ecological interactions and ecosystem stability. Studies have shown that multi-strata agroforestry and traditional homegardens can sustain species richness comparable to that of natural forests, often supporting 60–80% of the biodiversity found in adjacent native ecosystems. Such biologically diverse systems contribute not only to ecological resilience but also to sustained agricultural productivity.

Habitat and Connectivity

Trees serve as refuge areas between fragmented forest patches and also serve as habitats for birds and pollinators. This also contributes to landscape level ecological resilience.

Pollination services

Trees in agroforestry systems provide essential habitats and foraging resources for a wide range of pollinators, including bees, butterflies, birds, and other beneficial insects. By supporting these pollinator populations, agroforestry enhances pollination services within the farming landscape, which in turn contributes to improved fruit set, seed formation, and overall crop yields.

d. Cultural services:

Cultural ecosystem services contribute to human well-being beyond material benefits.

Aesthetic and recreational values: Agroforestry landscapes are visually attractive, supporting eco-tourism and rural recreation.

Traditional knowledge and cultural heritage: Many indigenous communities manage agroforestry systems as a part of their cultural practices. Examples: Homegardens in Kerala, *Prosopis cineraria*-based agroforestry in Rajasthan and Taungya systems in Southeast Asia.

Educational and research values: Agroforestry provides "living laboratories" to study the plant interactions, soil ecology and climate adaptation strategies.

Spiritual and religious values: Sacred groves, religious trees, and culturally important species (e.g., Ficus religiosa) support spiritual traditions.

Quantification of ecosystem services:

Quantification of the ecosystem services in agroforestry systems requires systematic, reliable, and scalable methodologies that capture the complex interactions between trees, crops, livestock, soil, and microclimate. Because ecosystem services operate across multiple spatial and temporal scales, quantification approaches range from field-based measurements and laboratory analyses to remote sensing, modeling tools, and participatory assessment methods. Quantification of major ecosystem services provided by the agroforestry systems are given below:

Quantification of provisioning services

Provisioning services include timber, fruits, fodder, fuelwood, fiber, resins, medicinal products, and NTFPs.

Timber and Fuelwood

Diameter at breast height (DBH) and total tree height are recorded to estimate standing volume, while species-specific wood density values are used to refine biomass calculations. These measurements are then converted into timber volume using allometric equations. Fuelwood quantification typically involves biomass sampling to determine the amount of harvestable wood, followed by assessment of its energy content (kcal kg^{-1}) to evaluate its calorific value and suitability for household or commercial use.

Fodder Yield

Fodder yield in agroforestry systems is quantified by measuring leaf biomass through systematic sampling, followed by laboratory analysis of nutritive value parameters such as crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Digestibility is further assessed using in vitro dry matter digestibility (IVDMD) tests to determine the overall feeding quality for livestock.

Fruit and NTFP Yield

Fruit and non-timber forest product (NTFP) yields are assessed through several complementary measurements. These include counting the number of fruits produced per tree and estimating total fruit biomass using standardized sampling methods. Seasonal yield tracking is conducted to capture variations across different harvesting periods. For NTFPs such as resins and gums, yield is quantified through systematic tapping and measurement of extracted material over defined intervals.

Carbon sequestration and climate regulation

Carbon sequestration includes carbon stored in aboveground biomass (AGB), belowground biomass (BGB), deadwood, litter, and soil organic carbon (SOC). Quantification involves:

Field measurement of tree biomass:

Diameter at Breast Height (DBH) and Height Measurements

These measurements feed into species-specific or generalized allometric equations, such as:

$$\mathbf{AGB = 0.0673 \times (\varrho D^2 H)0.976}$$

Where, ϱ = wood density, D = DBH, H = tree height.

Belowground biomass estimation

Because direct measurement of root biomass is destructive and labor-intensive, belowground biomass is typically estimated using established root-to-shoot ratios. These ratios vary by ecosystem type, with values generally ranging from 0.20–0.30 for tropical tree species and 0.25–0.40 for species growing in dry or arid regions. This approach provides a reliable approximation of belowground carbon stocks without disturbing the system.

Soil organic carbon (SOC) measurement

Soil organic carbon (SOC) is quantified through systematic soil sampling at multiple depth intervals, typically 0–15 cm, 15–30 cm, and 30–60 cm. Bulk density is determined for each depth to assess soil mass, while SOC concentration is measured using methods such as the Walkley–Black wet oxidation technique or dry combustion using a CN analyzer. SOC stock (Mg C ha^{-1}) is then calculated using the formula:

$$\textbf{SOC Stock = SOC\% × Bulk Density × Soil Depth}$$

Remote Sensing and GIS

Remote sensing facilitates landscape-level carbon estimation: Example LiDAR- accurate canopy height and structure, Sentinel-2 / Landsat 8- NDVI, EVI to infer biomass

Process-Based Models

- CO2FIX: carbon pools in trees, soil, wood products
- CENTURY and Roth C: SOC turnover

Soil conservation and erosion control

Soil conservation benefits are measured through indicators of erosion reduction, sediment yield, and soil structural stability.

Erosion plots and runoff measurements

Soil erosion under agroforestry systems is commonly assessed using standard runoff plots, typically 22.1 meters in length as recommended by USLE guidelines. These plots allow for the direct measurement of soil loss (Mg ha^{-1} $year^{-1}$), sediment concentration, and runoff volume. Employing a paired-plot design—comparing an agroforestry field with a nearby control plot under conventional management—provides stronger evidence by accounting for local environmental variability and enabling more accurate evaluation of erosion reduction benefits.

Soil physical properties

Soil physical properties provide important indicators of the conservation benefits of agroforestry systems. Key parameters assessed include bulk density, aggregate stability, infiltration rate—typically measured using double-ring infiltrometers—and soil penetration resistance. Compared to monocropping systems, tree-based agroforestry practices often lead to notable improvements in soil structure, with studies reporting 15–35% higher infiltration rates, 20–40% greater aggregate stability, and significantly reduced soil compaction.

Universal Soil Loss Equation (USLE/RUSLE)

$$A = R \times K \times LS \times C \times P$$

Agroforestry reduces soil erosion primarily through a substantial decrease in the C-factor, reflecting improved vegetative cover.

Remote sensing for soil erosion

- NDVI/SAVI: indicators of soil cover
- DEM (Digital Elevation Models): slope, LS factor
- Hydrological models: SWAT, WEPP for erosion simulation

Water regulation services

Agroforestry influences water infiltration, groundwater recharge, evapotranspiration, and water quality.

Infiltration and water holding capacity

- Double-ring infiltrometers
- Tension infiltrometers
- Pressure plate apparatus for soil moisture retention

Streamflow and groundwater monitoring

- Hydrometric stations
- Piezoelectric groundwater wells
- Automatic water level loggers

Water quality assessment

- Total suspended solids (TSS)
- Nitrate and phosphate concentrations
- Turbidity

Tree buffers significantly reduce nutrient leaching.

Hydrological Modeling

- SWAT (Soil and Water Assessment Tool)
- MIKE-SHE
- InVEST Water Yield Model

Simulate effects of agroforestry on watershed hydrology.

Biodiversity enhancement

Vegetation surveys

- Quadrat sampling (1 m^2, 10 m^2, 100 m^2)

- Tree inventory: species richness, Shannon–Wiener Index
- Basal area and canopy cover measurements

Soil microbial diversity

- Soil respiration tests
- Microbial biomass carbon (fumigation–extraction)
- DNA-based methods: qPCR, metagenomics
- Enzyme assays (dehydrogenase, phosphatase)

Pollinator and insect biodiversity

- Sweep nets
- Pitfall traps
- Flower visitation counts
- Malaise traps

Bird and mammal surveys

- Point counts
- Line transects
- Camera traps

Biodiversity Modeling

- Shannon Index (H')
- Simpson Index (D)
- Sørensen similarity index

Microclimate Regulation

Temperature and humidity measurement

- Data loggers (HOBO, Tinytag)
- Thermal infrared cameras

Measurements include:

- Air temperature
- Soil temperature
- Relative humidity
- Vapor pressure deficit

Agroforestry typically reduces field temperatures by 1–5°C.

Wind speed reduction

- Cup anemometers
- Ultrasonic wind sensors

Radiation Interception

- PAR sensors (Photosynthetically Active Radiation)
- Ceptometers

Nutrient cycling

Nutrient cycling (especially N, P, and K) is enhanced by litterfall, root turnover, and nitrogen fixation.

Litterfall measurement

Litter traps (0.25–1 m^2) are placed under tree canopies to measure:

- Litter quantity (kg dry matter ha^{-1})
- Nutrient content (N, P, K, Ca, Mg)

A single tree may contribute 10–20 kg of leaf litter annually.

Nutrient return analysis

Laboratory analysis of dried litter for:

- Total nitrogen (Kjeldahl method)
- P and K (acid digestion followed by ICP/OES analysis)

Nitrogen fixation quantification

- Acetylene reduction assay (ARA)
- ^{15}N natural abundance method
- N-difference method

Soil Nutrient Analysis

- Available N (alkaline permanganate)
- Available P (Olsen or Bray method)
- Available K (flame photometry)
- CEC and pH

Socioeconomic and cultural services

Household surveys and participatory tools

Used to assess:

- Cultural importance
- Traditional knowledge
- Perceived ecosystem service benefits

Tools include:

- PRA (Participatory Rural Appraisal)
- Likert-scale ranking
- Benefit–cost analysis

Methods for monetary valuation

Valuing ecosystem services in agroforestry systems is essential for translating ecological functions into economic and social terms that can inform policy, investment decisions, and land-use planning. Since agroforestry generates a diverse portfolio of provisioning, regulating, supporting, and cultural services, valuation methods must account for both market and non-market benefits. Broadly, valuation methods fall into four categories: market-based approaches, cost-based approaches, revealed-preference methods, and stated-preference methods, complemented by benefit transfer where primary valuation is not feasible.

Market-based valuation

Market-based valuation estimates the value of ecosystem services using existing market prices, particularly for provisioning goods. The direct market price method assigns economic value to products such as timber, fruits, fodder, fuelwood, latex, resins, medicinal plants, and other NTFPs based on actual market transactions—for example, timber priced per cubic meter, fodder per kilogram of dry matter, and fruits or NTFPs according to seasonal rates. While simple and widely applicable, this method is limited to goods with established markets. Additionally, some regulating services, such as carbon sequestration, now have emerging markets where carbon credits from agroforestry systems can be valued using voluntary or compliance market prices (USD per tCO_2e).

Cost-based valuation methods

Cost-based valuation estimates the worth of ecosystem services by assessing the costs that are avoided, replaced, or prevented due to the presence of agroforestry. The avoided cost method values ecosystem functions such as reduced soil erosion, which lowers dredging expenses, or tree shade that decreases irrigation requirements. The replacement cost method estimates how much it would cost to substitute natural services with man-made solutions—for example, comparing the cost of constructing check-dams or contour bunds with the natural soil stabilization provided by trees, or contrasting artificial windbreaks with agroforestry shelterbelts. The damage cost avoided approach assigns value to services that prevent losses, such as reduced crop failure or minimized soil nutrient depletion due to agroforestry practices.

Revealed-preference methods

Revealed-preference valuation derives the economic value of ecosystem services from people's actual behavior in related markets. The Hedonic Pricing Method (HPM) captures how agroforestry-driven improvements—such as enhanced microclimate, shade, or landscape aesthetics—increase farmland or property values. The Travel Cost Method (TCM) is used to assess cultural or recreational services, where the expenses incurred by visitors to agroforestry parks or biodiversity-rich landscapes indicate the recreational value of these ecosystems.

Stated-Preference Methods

Stated-preference methods play a crucial role in valuing non-market ecosystem services such as biodiversity conservation, cultural benefits, landscape aesthetics, and carbon sequestration. The Contingent Valuation Method (CVM) employs structured surveys to assess individuals' willingness to pay for improvements or willingness to accept compensation for losses in ecosystem services, such as enhanced tree-based watershed protection or biodiversity conservation in agroforestry systems. Choice Experiments (CE), on the other hand, present respondents with alternative scenarios featuring varying attributes—such as carbon storage, erosion control, or habitat enhancement—to estimate the marginal value of each ecosystem service component.

Benefit transfer method

The benefit transfer method is used when conducting primary valuation is impractical, allowing researchers to apply ecosystem service values derived from previous studies to comparable ecological and socio-economic contexts. This approach may involve unit value transfer, such as applying per-hectare carbon sequestration values; function transfer, where valuation equations or models are adapted to new conditions; or meta-analysis transfer, which synthesizes results from multiple studies to generate more robust estimates. Although cost-effective and widely adopted in large-scale assessments, benefit transfer requires careful calibration to account for variations in ecosystem characteristics, local socio-economic conditions, and policy environments to ensure accuracy and relevance.

Valuing regulating ecosystem services

The benefit transfer method is used when primary valuation is not feasible, allowing existing valuation results from previous studies to be applied to similar ecological and socio-economic contexts. This approach may involve unit value transfer, such as applying per-hectare carbon values; function transfer, where valuation equations are adapted to a new setting; or meta-analysis transfer, which synthesizes findings from multiple studies to generate more robust estimates.

Valuation of biodiversity and habitat services

Biodiversity in agroforestry contributes to pest regulation, pollination, and ecological stability. Valuation approaches include a. Replacement cost for natural pest control,

b. Market value of pollinator-dependent crop productivity and c. Stated-preference methods for habitat conservation values

Valuation of cultural and social ecosystem services

Cultural services such as traditional knowledge, spiritual values, aesthetics, and recreation are difficult to quantify monetarily.

- CVM and CE surveys for cultural landscapes
- Travel cost method for recreational sites
- Sociocultural valuation through PRA tools, ranking methods, and stakeholder interviews

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Experimental Designing and layout, software's, and data analysis in agroforestry research

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Introduction

Agroforestry is a collective term for land-use systems in which woody perennials such as trees, fruit trees, bamboos, or shrubs are deliberately grown on the same piece of land with crops and sometimes livestock, either in a spatial arrangement or temporal sequence. It integrates the ecological and economic interactions of different components, thereby enhancing productivity, resilience, and sustainability. Sound experimental design and data analysis are essential to ensure valid, reproducible, and interpretable results in agroforestry research.

Experimental Designs in Agroforestry Research

Any scientific investigation involves formulation of certain hypotheses whose validity is examined through the data generated from an experiment conducted for the purpose. Thus, experimentation becomes an indispensable part of every scientific activity and designing an experiment is an integrated component of every research programme. Designing and analyzing an experiment are closely linked processes. A good design not only ensures the efficient collection of data but also facilitates valid statistical analysis. Three fundamental principles form the basis of all experimental designs:

- **Replication -** Replication is the repetition of the treatments under investigation to different experimental units.
- **Randomization** – It is the allocation of the treatments to the experimental units in a manner such that each experimental unit has an equal chance of receiving any of the treatment.
- **Local Control** – Dividing heterogeneous experimental material into homogeneous groups (blocks) to minimize the effect of uncontrolled variation.

Replication and local control increase the precision of an experiment, while randomization ensures unbiased estimation of treatment effects. Various experimental designs have been employed in conducting investigations in agroforestry. The choice of an experimental design depends on the objectives of the experiment and the number of factors to be investigated. Factors are the variables whose influence on a response variable is being studied in the experiment. If only one factor is being studied in an experiment, then such an experiment is called a single factor experiment (e.g. CRD, RBD, LSD). If more than one factor is being studied simultaneously in an experiment, then such an experiment is called multi-factor experiment (e.g. Factorial Experiments, Split-Plot, and Strip-Plot Experiments).

Once the experimental results are obtained, they must be systematically analyzed and interpreted to draw valid conclusions. The primary role of statistics in experimental design is to partition the observed variation in data into components attributable to known causes (treatments or factors) and those arising from random or uncontrolled fluctuations. The Analysis of Variance (ANOVA), introduced by R. A. Fisher, is the classical and most widely used statistical technique for this purpose. ANOVA helps determine whether the differences among treatment means are statistically significant or merely due to random variation. In essence, the basic objective of ANOVA is to test the homogeneity of several means.

Assumptions of ANOVA

- Observations are independent
- Effects of different factors are additive
- Errors are independently and identically distributed
- Errors have constant variance
- Errors are normally distributed

With this understanding of ANOVA and its assumptions, the following section illustrates some commonly used experimental designs in agroforestry research, along with their layouts and examples.

Completely Randomized Design (CRD)

This is used when the experimental units exhibit homogeneity. This is a design in which only randomization and replication are used and there is no use of local control here. Number of replications for each treatment need not be equal. Treatments are assigned randomly to the experimental units. Often used in greenhouse, nursery, and laboratory experiments where experimental conditions are uniform.

Example: To study the effect of different organic manures on growth of tree seedlings in a nursery.

If an experiment includes four treatments (T1- Farmyard Manure (FYM), T2- Vermicompost, T3- Poultry Manure, T4- Control) with four replications, and their random allocation to the nursery pots in a Completely Randomized Design is shown in the layout below.

T2	T1	T1	T3
T3	T2	T3	T2
T4	T4	T2	T1
T4	T3	T1	T4

Model: $y_{ij}=\mu+\tau_i+e_{ij}$, $i=1, \ldots, t$, $j=1, \ldots, r_i$, $\sum_i r_i=n$

y_{ij} is the observation from i^{th} treatment and j^{th} replicates, μ is the general mean, τ_i is the i^{th} treatment effect, e_{ij} is the error component

Hypothesis: H_0: All treatment means are equal
H_1: At least one pair of treatment means are not equal

ANOVA Table:

Source of Variation	df	SS	MS	F
Treatment	t-1	SST	MST= SST/(t-1)	MST/MSE
Error	n-t	SSE	MSE=SSE/(n-t)	
Total	n-1	TSS		

When treatment effects are significant, post-hoc (multiple comparison) tests are used to identify the best treatments. Common tests include LSD (Least Significant Difference), Duncan's Multiple Range Test (DMRT), Tukey's HSD.

Randomized Block Design (RBD)

The most widely used design in agroforestry experiments is randomized complete block design (RCBD) or randomized block design (RBD). In many experiments, besides treatments the experimental material is a major source of variability in the data. When the experimental units are heterogeneous, a part of the variability can be accounted for by grouping the experimental units in such a way that experimental units within each group are as homogeneous as possible. Blocking is the arranging of experimental units in groups (blocks) that are similar to one another. The treatments are then allotted randomly to the experimental units within each group (or blocks). Every treatment appears once in every block.

Example: To study the growth and productivity of different intercrops grown under a tree plantation.

If an experiment includes four intercrops (treatments) such as T1-Maize, T2-Cowpea, T3-Blackgram, T4-Greengram each with four replications under a teak plantation, their allocation to each replicate or block in a Randomized Block Design is shown in the layout below.

Block 1	Block 2	Block 3	Block 4
T3	T2	T4	T1
T4	T1	T2	T3
T1	T3	T1	T2
T2	T4	T3	T4

Model: $y_{ij} = \mu + \tau_i + \beta_j + e_{ij}\ ,\ \ i = 1, \dots, t,\ \ j = 1, \dots, r,\ \ n = r \times t$

y_{ij} is the observation from i^{th} treatment and j^{th} replicate, μ is the general mean, τ_i is the i^{th} treatment effect, β_j is the j^{th} block or replicate effect, e_{ij} is the error component

Hypothesis: For testing Treatment effect

- H_0: All treatment means are equal
- H_1: At least one pair of treatment means are not equal

ANOVA Table:

Source of Variation	df	SS	MS	F
Blocks (Replication)	r-1	SSB	MSB= SSB /(r-1)	MSB/MSE
Treatment	t-1	SST	MST= SST/(t-1)	MST/MSE
Error	(t-1)*(r-1)	SSE	MSE=SSE/[(t-1)*(r-1)]	
Total	rt-1	TSS		

When treatment effects are significant, post-hoc (multiple comparison) tests are used to identify the best treatments. Common tests include LSD (Least Significant Difference), Duncan's Multiple Range Test (DMRT), Tukey's HSD.

Factorial Experiments

Only one factor is involved in CRD and RBD. However, more than one factor will often need to be studied simultaneously. Such experiments are known as factorial experiments. The treatments in factorial experiments consist of two or more levels of the two or more factors. These experiments provide an opportunity to study not only the individual effects of the factors but also their interactions. A factorial experiment can be laid out in any basic design such as CRD, RBD, or LSD, depending on the experimental conditions

Example: To study the effects of two factors such as plant spacing (Factor A) and planting age (Factor B) on the growth of bamboo in an agroforestry system. If factor A has two levels (A1, A2) and factor B has three levels (B1, B2, B3), there will be six treatment combinations. If each treatment combination is replicated three times, the layout of this two-factor factorial experiment arranged in RBD is shown below.

Replication 1	Replication 2	Replication 3
A1B1	A2B1	A1B2
A1B2	A1B3	A2B3
A2B3	A1B1	A2B1
A2B2	A2B2	A1B3
A1B3	A2B3	A1B1
A2B1	A1B2	A2B2

ANOVA Table for two factor factorial experiment with r replication in RBD

Source of Variation	df	SS	MS	F
Replication	r-1	SSR	MSR=SSR/(r-1)	MSR/MSE
Treatments	ab-1	SST	MST= SST/(ab-1)	MST/MSE
A	a-1	SSA	MSA= SSA/(a-1)	MSA/MSE
B	b-1	SSB	MSB= SSB/(b-1)	MSB/MSE
AB	(a-1)*(b-1)	SSAB	MSAB= SSAB/[(a-1)*(b-1)]	MSAB/MSE
Error	(r-1)*(ab-1)	SSE	MSE=SSE/[(r-1)*(ab-1)]	
Total	rab-1	TSS		

Factor A has a level, Factor B has b levels

When treatment effects are significant, post-hoc (multiple comparison) tests are used to identify the best treatments. Common tests include LSD (Least Significant Difference), Duncan's Multiple Range Test (DMRT), Tukey's HSD.

Split-Plot Design

The split-plot design is particularly suitable for two-factor experiments where the levels of one factor require larger plot sizes or more difficult operations than the other. In such cases, the experiment consists of a set of main plots, to which the levels of the main-plot factor are assigned, and each main plot is subdivided into subplots, to which the levels of the subplot factor are assigned. This design sacrifices precision in estimating the effects of the main-plot factor to gain higher precision for the subplot factor.

Example: To study the effect of irrigation levels (Factor A) and fertilizer doses (Factor B) on intercrop yield in agroforestry system**.** In this experiment, irrigation levels, which require larger plot areas and are difficult to change frequently, were assigned to the main plots, while fertilizer doses, which can be applied more easily, were assigned to the subplots. Suppose the experiment consisted of two levels of irrigation (A1 and A2) and three levels of fertilizer dose (B1, B2, B3). The entire field is to be divided into three replications, each containing two main plots. The two levels of Factor A are randomized among the main plots within each replication. Each main plot then subdivided into three subplots, to which the three levels of Factor B are assigned at random. The layout of this experiment is shown below.

Replication 1

B1	B3
B3	B1
B2	B2
A1	A2

Replication 2

B3	B2
B1	B1
B2	B3
A2	A1

Replication 3

B3	B1
B2	B3
B1	B2
A1	A2

ANOVA Table

Source of Variation	**df**	**SS**	**MS**	**F**
Replication	r − 1	SSR		
Main-plot Factor (A)	a − 1	SSA	MSA	MSA / MSEa
Error (a) (Main-plot error)	(r−1)(a−1)	SSEa	MSEa	
Subplot Factor (B)	b − 1	SSB	MSB	MSB / MSEb
A × B Interaction	(a−1)(b−1)	SSAB	MSAB	MSAB / MSEb

Error (b) (Subplot error)	a(r−1)(b−1)	SSEb	MSEb	
Total	rab − 1	TSS		

a = levels of Factor A (main-plot factor), b = levels of Factor B (subplot factor), r = number of replications

When treatment effects are significant, post-hoc (multiple comparison) tests are used to identify the best treatments.

Analysis of Experimental Designs Using R Software

Many statistical software is available for designing experiments and analyzing data in agricultural and agroforestry research. Here the analysis procedure has been illustrated using R statistical software (RStudio), which is a freely available and widely used open-source platform for data analysis and visualization.

Analysis of Completely Randomized Design (CRD)

```
# Create data for a Completely Randomized Design (CRD)
# 5 Treatments (T1–T5) × 5 Replications = 25 observations
Treatment <- rep(c("T1", "T2", "T3", "T4", "T5"), each = 5)
# Example yield values
Yield <- c(108.2, 112.7, 116.8, 106.8, 117.9,215.4, 220.6, 218.2, 225.3, 221.5,
        188.4, 190.3, 195.2, 193.6, 197.5,186.1, 188.6, 190.8, 187.9, 191.2,
        214.3, 226.2, 215.0, 230.6, 218.6)
# Combine all into one data frame
crd_data <- data.frame(Treatment, Yield)
# Convert Treatment column to factor
crd_data$Treatment <- as.factor(crd_data$Treatment)
#Fit Linear Model and Perform ANOVA
model_crd <- lm(Yield ~ Treatment, data = crd_data)
# Perform ANOVA using anova() function
anova_result <- anova(model_crd)
anova_result
Analysis of Variance Table
Response: Yield
          Df  Sum Sq  Mean Sq  F value   Pr(>F)
Treatment  4   39235   9808.8   455.03   < 2.2e-16 ***
Residuals 20   431     21.6
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Interpretation:

Treatment effect is significant ($p < 0.05$)

```
### Treatments Comparison (LSD Test)
# Load agricolae package
library(agricolae)
# Perform LSD test
LSD_result <- LSD.test(model_crd, "Treatment")
LSD_result
$statistics
 MSerror  Df   Mean      CV         t.value      LSD
 21.5564  20  187.108  2.481394  2.085963  6.125264
$parameters
      test      p.ajusted   name.t    ntr   alpha
 Fisher-LSD     none    Treatment   5     0.05
$groups
     Yield   groups
T5  220.94     a
T2  220.20     a
T3  193.00     b
T4  188.92     b
T1  112.48     c
```

Interpretation:

- CD value =6.125264 at 5% Level of significance
- Treatments with the same letter are not significantly different

3.2 Analysis of Randomized Block Design (RBD)

```
# Create data for a Randomized Block Design (RBD)
# 5 Treatments (T1–T5) × 5 Replications = 25 observations
Treatment <- rep(c("T1", "T2", "T3", "T4", "T5"), times = 5)
Replication <- rep(1:5, each = 5)
# Example yield values
Yield <- c(98, 118, 138, 158, 178,   102, 122, 142, 162, 182,
  99, 119, 139, 159, 70, 101, 121, 141, 161, 181,
  100, 120, 140, 160, 180 )
# Combine all  into one data frame
rbd_data <- data.frame(Replication,Treatment, Yield)
# Convert Replication & Treatment column to factor
```

```
rbd_data$Replication<-as.factor(rbd_data$Replication)
rbd_data$Treatment<-as.factor(rbd_data$Treatment)
#Fit Linear Model and Perform ANOVA
model_rbd <- lm(Yield ~ Replication+Treatment, data = rbd_data)
# Perform ANOVA using anova() function
anova_result <- anova(model_rbd)
anova_result
     Analysis of Variance Table
Response: Yield
                 Df  Sum Sq   Mean Sq   F value   Pr(>F)
Replication      4   2169.0    542.2     1.1410    0.372781
Treatment        4   13181.0   3295.2    6.9338    0.001949 **
Residuals        16  7603.8    475.2
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Interpretation:

Treatment effect is significant ($p < 0.05$)

Treatments Comparison (LSD Test)

```
# Load agricolae package
library(agricolae)
# Perform LSD test
LSD_result <- LSD.test(model_rbd, "Treatment")
LSD_result
$statistics
  MSerror   Df   Mean     CV         t.value    LSD
  475.24    16   135.64   16.07196   2.119905   29.22826
$parameters
     test         p.ajusted   name.t      ntr   alpha
  Fisher-LSD      none        Treatment   5     0.05
$groups
    Yield groups
T4  160.0   a
T5  158.2   a
T3  140.0   ab
T2  120.0   bc
T1  100.0   c
```

Interpretation:

- CD value =29.22826 at 5% Level of significance
- Treatments with the same letter are not significantly different

3.3 Analysis of Two Factor Factorial RBD

```
# Two-factor factorial in RBD: A (3 levels) × B (2 levels) × 3 replications = 18 obs
#Define factors
A <- rep(rep(c("A1","A2","A3"), each = 2), times = 3)
B <- rep(c("B1","B2"), times = 9)
Replication <- rep(1:3, each = 6)
# Example yield values
Yield <- c(82, 90,   94, 102,   106, 118,   84, 91,   96, 103,   108, 120, 83, 92,   95, 104,
107, 121)
# Create dataframe
fact_data <- data.frame(Replication,A,B,Yield)
#convert Replication, A and B column to factor
fact_data$Replication<-as.factor(fact_data$Replication)
fact_data$A<-as.factor(fact_data$A)
fact_data$B<-as.factor(fact_data$B)
#Fit Linear Model and Perform ANOVA
model_fact <- lm(Yield ~ Replication +A+B+A:B, data = fact_data)
# Perform ANOVA using anova() function
anova_result<-anova(model_fact)
anova_result
Analysis of Variance Table

Response: Yield
             Df  Sum Sq   Mean Sq   F value    Pr(>F)
Replication  2   11.11    5.56      15.625     0.0008373 ***
A            2   2085.78  1042.89   2933.125   1.427e-14 ***
B            1   410.89   410.89    1155.625   1.148e-11 ***
A:B          2   21.78    10.89     30.625     5.446e-05 ***
Residuals    10  3.56     0.36
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Interpretation:

- Effect of Factor A is significant
- Effect of Factor B is significant

• Interaction of AB is significant

Treatments Comparison (LSD Test)

```
library(agricolae)
# LSD for main effects
LSD_A <- LSD.test(model_fact, "A")
LSD_A
$statistics
   MSerror   Df    Mean        CV          t.value     LSD
  0.3555556  10   99.77778   0.5976128   2.228139   0.7670706

$parameters
       test       p.ajusted  name.t   ntr   alpha
  Fisher-LSD     none       A        3     0.05
$groups
      Yield     groups
A3  113.3333    a
A2   99.0000    b
A1   87.0000    c

LSD_B <- LSD.test(model_fact, "B")
$statistics
   MSerror   Df    Mean        CV          t.value     LSD
  0.3555556  10   99.77778   0.5976128   2.228139   0.6263106

$parameters
       test       p.ajusted   name.t   ntr   alpha
  Fisher-LSD     none         B       2     0.05
$groups
       Yield    groups
B2  104.5556     a
B1   95.0000     b
# LSD for interaction (AB)
LSD_AB <- LSD.test(model_fact, c("A","B"))
LSD_AB
$statistics
   MSerror   Df    Mean       CV           t.value     LSD
  0.3555556 10    99.77778   0.5976128   2.228139   1.084802
```

```
$parameters
      test       p.ajusted   name.t   ntr   alpha
 Fisher-LSD     none       A:B      6     0.05
$groups
           Yield     groups
A3:B2   119.6667      a
A3:B1   107.0000      b
A2:B2   103.0000      c
A2:B1    95.0000      d
A1:B2    91.0000      e
A1:B1    83.0000      f
```

Interpretation:

- Treatments with the same letter are not significantly different

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Integrating Genomics for Tree Improvement: Opportunities and Challenges

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Introduction

In the past, improving the forest productivity and adaptability relied on conventional tree breeding such as plus tree selection, provenance selection, progeny testing and clonal propagation (Zobel & Talbert, 1984; FAO, 2020). These conventional breeding methods played a crucial role in the genetic improvement of various tree species like *Dalbergia sissoo, Tectona grandis, Azadirachta indica, Populus sp, Eucalyptus sp, Casurina sp, and Leucaena sp*. However, the advancements made are limited by genotype and environmental interaction (GxE), long generation period, and high heterozygosity (Grattapaglia & Kirst, 2008; Kumar & Chaturvedi, 2016). It is important that integrating molecular techniques such as markers and multi-omics, would hasten the breeding efforts. These tools will enhance the selection process and effectively dissect the complex traits. This rapid tree breeding is a need of the hour due to increasing population, limited land resources and deforestation (Rajarajan et al. 2021). As for the availability of many important multipurpose tree species, whole-genome reference assemblies are available. Particularly like Populus (Tuskan et al., 2006), Eucalyptus (Myburg et al., 2014), Neem (Krishnan et al., 2012), Teak (Yashodha et al., 2019). etc. These genomic data provide crucial information on various traits of interest, such as wood, secondary metabolites and other associated characters. Based on the genomic information and genotypic data, tree breeders can easily predict the phenotypes (Isik, 2014; Resende et al., 2012). For instance, genomic predictions in Eucalyptus have reduced half of the breeding cycle and made it possible to identify the superior individual for growth and wood quality characters without field trials (Resende et al., 2012; Grattapaglia, 2017). In addition, the GWAS approach in Populus has enabled to identification of the key genes involved in lignin biosynthesis for pulp and paper industries (Porth et al., 2013). With multiple research studies emphasising stress-responsive transcriptome profiling in economically important species, the use of genomics in tree improvement is gaining popularity in India. The transcription factors for adaptivity, such as WRKY, NAC, and DREB, were identified in *Melia dubia* under drought stress (Naithani et al., 2021). Similarly, salinity-responsive genes have been found in *Casuarina equisetifolia,* which may be useful for molecular breeding of coastal agroforestry species (Ramesh et al., 2019). These findings would be more effective with genome-editing technologies like CRISPR/Cas, which aid in creating climate-resilient varieties for drought-prone areas (Jaganathan et al., 2018). Furthermore, conservation genomics has been progressively applied for genetic conservation and utilization of high-value tree species such as Indian sandalwood and red sanders, supporting the screening of superior genetic resources for a range of ecological conditions (De Kort et al., 2022). Despite its importance, applying genomics in forestry improvement remains a challenge. This is due to the large genome size, high repetitive elements, which makes the annotation and assembly complexity (Plomion et al., 2018). Unlike developing mapping populations and controlled crossings in crops, it is highly challenging in trees (Isik, 2014). In addition, traits like wood density, heartwood establishment and pest resistance in several economically important trees, the genomic model prediction is declined as these traits are highly quantitative in nature and strongly influenced by the environment (Beaulieu et al., 2014). Another major challenge in developing countries is the lack of public-private sector computational and bioinformatics infrastructures (Kumar & Chaturvedi, 2016). Therefore, the policy and regulatory frameworks are important, which necessitate a balanced approach between productivity and ecological sustainability (Ratnam et al., 2014). It is important to understand that genomics works better when it's in combination with conventional breeding. Genomics can be a decision-support tool within an intensified phenotypic field evaluation. For instance, like genomic selection in Scandinavian conifers (Westbrook et al., 2020), genomic-assisted Eucalyptus breeding in Brazil (Grattapaglia, 2017), and teak genetic improvement programs in Kerala (Shaji et al., 2019).

Therefore, the use of genomics in tree improvement could aid in boosting climate resilience forestry, rapid genetic gain and sustainable supply of forest products such as timber, and other non-timber forest products for the industries. On the other hand, it is important that interdisciplinary as molecular biologists, tree breeders, data scientists, and forestry specialists, are required for successful implementation.

Applications of genomics in tree breeding

Recently, genomic tools have served to understand, manipulate and accelerate the genetic gains in forest tree species (Neale & Kremer, 2011). Integrating genomics into tree breeding provides many opportunities, such as trait improvement and its inheritance, and selection of superior elite germplasm. MAS basically exploit non-random association (linkage disequilibrium; LD). The efficiency of MAS is based on the density of markers in the vicinity of relevant QTLs and the extent of LD between markers and causal QTLs (Muranty et al., 2014). Early stage of domestication in the trees is an advantage in terms of the genetic variation available for selection, causing

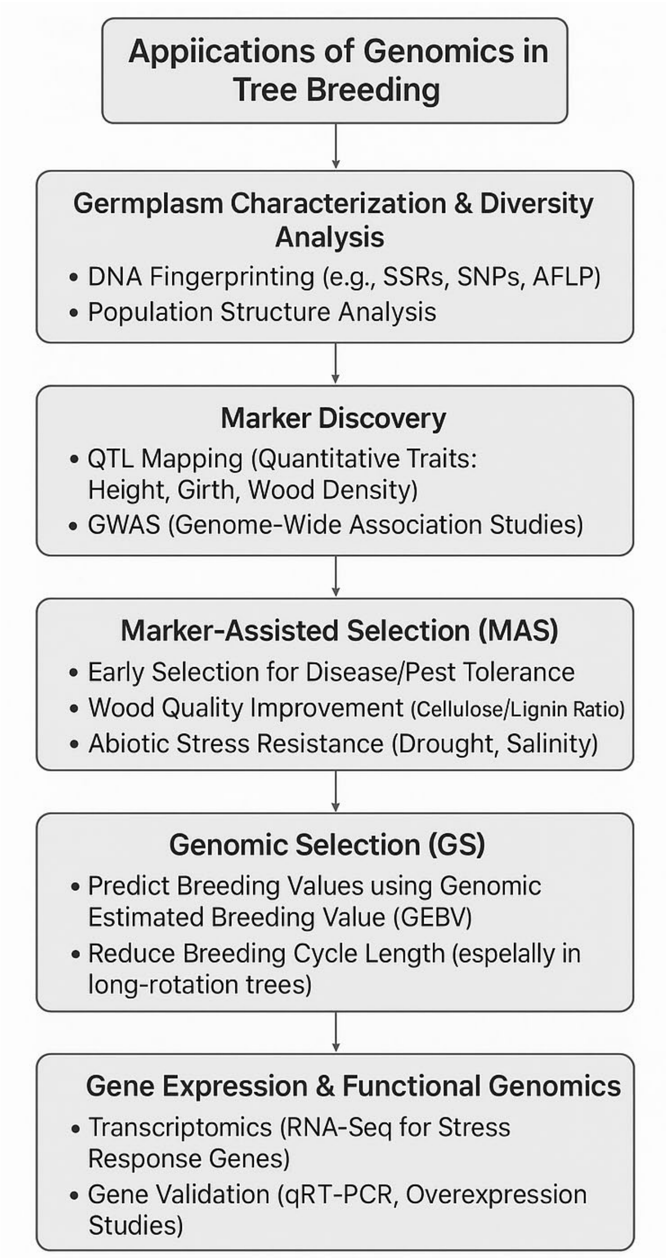

Figure. 1. Schematic diagram of applications of genomics in tree breeding

-low LD (Neale and Savolainen, 2004). Low LD and large effective population sizes in base breeding populations are disadvantageous for MAS. Due to these limitations, MAS is expected to be more efficient after narrowing the genetic diversity in trees, which would increase linkage disequilibrium. With the accessible marker densities, MAS would be valuable for selection within full-sib or half-sib families. This would be good for species where clonal placement obtained by cuttings is common (Populus spp. and Eucalyptus spp.). Indeed, this would involve the selection of a few promising families in which marker-QTL associations can be assessed for use in MAS. Hospital et al. (2009) propose five MAS breeding applications: (i) population screening, (ii) gene pyramiding, (iii) marker-assisted backcrossing, (iv) marker-based recurrent selection and (v) selection based on a combination of molecular and phenotypic data. Marker-assisted backcross is found to be the most common application. Among trees, shrubs and perennials (*Carica papaya, Manihot esculenta, Coffea arabica, Malus sp., Prunus sp., Pyrus pyrifolia, Rubus idaeus, Rosa sp., Simmondsia chinensis, Vitis vinifera*), most work in markers is found in apple trees.

Inclusion of genomic selection strategy into the present and future breeding program can aid in the evaluation of genomic breeding values and selection of suitable tree genotypes for plantation programs to achieve the estimated yield (Rajarajan et al. 2021). Additionally, DArT, ddRAD and WGRS contributed to developing sequence-based markers in tree genomics through draft genome assembly data, which can be employed in GWAS, marker-assisted selection and genomic selection to deliver genetically improved cultivars (Yashodha et al. 2019; Mahesh et al. 2022). Also, it is highly suggested to select all or multiple trait-associated QTLs. This is where genomic selection plays a significant role by capturing numerous useful genes with small additive effects in tree breeding. A sudden rise in feasible sequencing technologies and high-throughput Phenotyping facilities is paving the way for the implementation of genomic selection to improve tree germplasm. Genotypic and phenotypic data analysis of a 'training population' allows the prediction of genomic estimated breeding values (GEBVs) that can be further used for genomic selection (Meuwissen et al. 2001). This is a practical roadmap for enhancing selection efficiency in trees by reducing the number of breeding cycles, obviating the required phenotyping for successive selection, thus lowering the time and cost, leading to increased genetic gains. To bridge the genotype-phenotype research gap through the utilization of genomic resources. High-throughput genotyping-based genomic prediction, in addition to accurate phenotyping data, is essential for successful genomic selection in breeding.

The availability of genome sequencing data facilitates identifying genes, alleles, and QTLs underlying key traits through functional genomics and/or GWAS-based approaches. Candidate genes and gene families can be characterised using in silico tools such as domain architecture analysis, expression profiling in publicly available RNA-seq data, homology modelling, etc. These exercises allow pinpointing the candidate genes, which can further be functionally characterised to elucidate their role in a particular trait. An alternate approach involves genotyping-by-sequencing, wherein the population has to be phenotyped for the given trait, and their genomes have to be sequenced to identify SNPs. The phenotyping and genotyping data are then statistically associated with identifying the high-confidence SNPs linked to traits, and the underlying genes, alleles, or QTLs can further be identified for functional characterisation. RNA-seq served as an alternate tool to identify the genes in species for which genome sequence information is not available. De novo assembly of transcriptome sequences did not require any reference genome. Therefore, it facilitated identifying novel genes expressed at a particular stage or time-point (of sampling) (Krishnan et al. 2012; Yasodha et al. 2018). Comparing the transcriptomes of different cultivars within the same species also enabled the identification of SNPs, which can further be used as potential markers for trait association. Also, scanning the RNA-seq reads for microsatellite motifs results in identifying SSR markers useful for genotyping purposes.

Challenges in Integrating Genomics for Tree Breeding

No doubt, the application of genomics in tree improvement provides an outstanding scope for rapid genetic gain achievement and improving complex traits. However, despite its potential, particularly practical tree improvement, several challenges hinder its full potential. These challenges include tree biology, genomic tools technical feasibility, and policy-related constraints. Although it is very important to have an improved understanding of its challenges for effective implementation.

Figure. 2 Challenges of implementing genomics in tree breeding

1. Long generation and complex life cycles

The major bottleneck in tree breeding is the inherently long gestation cycle for most tree species. Trees take several years to decades for their maturity. Under these circumstances, even genomic selection and marker-assisted selection would be time-consuming with respect to their validation. On the other hand, predicting seedlings may be limited, particularly the traits expressed in the late developmental stages, such as wood density and biotic resistance.

2. Large and complex genomes

Many of the tree species which are holding economic value, such as Pinus, Populus, and Eucalyptus, have a large genome size with high repetitive elements pose difficulties in sequencing, assembly and annotation (Müller et al., 2020). Additionally, many species are of a polyploid nature further complicates the identification of functional genes and QTLs. These are the major challenges of utilising genomic tools in the development of reliable markers.

3. Limited genomic resources

Many of the tropical tree species have no genomic information available. The absence of a reference genome influences the applicability of MAS and GS in these species (Neale & Kremer, 2011). Developing these resources is often costlier and time-consuming, particularly in developing countries.

4. Environmental interactions and phenotypic plasticity

Due to phenotypic plasticity, the particular genotype may perform differently under varying environmental regimes; under such situations, applying genomic predictive models remains challenging (Resende et al., 2012).

5. High costs and resources

Generally, many genomic approaches are costlier and consume more resources as computational infrastructure, resource persons, and research data analysts. Especially in developing countries, many of these constraints are very common. Many of the forestry research institutes in these countries have a lack of funding or are scant.

6. Data management and bioinformatics challenges

Massive datasets will be generated by genomic approaches such as high-throughput sequencing, SNP genotyping, and transcriptomic profiles. This enormous dataset storage and analysis require high infrastructure resources and analytic skills, respectively (Müller et al., 2020). Inadequately trained personnel and computational resources hinder the analysis and interpretation.

7. Regulatory, Ethical, and Social Considerations

Some of the genomic approach applications require regulatory clearance, such as genetic engineering and genome editing. Particularly, genetically modified trees and other intellectual properties could limit its scope (Neale & Kremer, 2011). Moreover, policies governing forest biodiversity conservation may limit the deployment of genetically modified or edited trees, even if they show superior performance.

Opportunities in Integrating Genomics for Tree Breeding

Integration of genomics applications into tree breeding would enhance the forest productivity, resilience and sustainable forest resources. One of the major opportunities is the rapid selection of elite tree germplasm for the target trait. More importantly, genomic selection and marker-assisted selection would aid breeders in predicting the desirable traits at the seedling stage itself, which in turn reduces time and resources and thereby reduces the breeding cycle.

Genomics studies provide opportunities like genome-wide association studies (GWAS) and functional genomics reveal the complex trait associations and their genetic control and genes; pathways related to growth, secondary metabolites, wood formation and stress resistance.

Effective molecular markers can accurately genotype the individuals and provide a detailed population structure and its genetic diversity for effective conservation and utilisation. This will help in maintaining heterozygosity and design effective strategies for tree breeding.

The genomic resources are crucial for future tree improvement through various biotechnological approaches, such as genome editing and genetically modified trees. These tools have potential for improved growth, other economic traits, resistance and adaptability. Overall, genomics in tree breeding provides many valuable opportunities to hasten the tree breeding strategies and improve understanding of genotype and phenotype association, which will be utilised in the tree improvement programmes.

Conclusions

Tree genomics will play a major role in the near future for understanding tree system biology and developing policy actions to conserve nature and manage forest genetic resources. In this context, research in terms of tree production, biotic and abiotic stress management, and restoration through tree genomics can be a game-changer. The management of tree genetic resources is critical in providing the contrasting alleles to maintain genetic diversity in genetic improvement programmes. In this circumstance, developing a complete genome sequence of various trees could help in the functional analysis of genome components to use as an efficient tool for tree breeding. Therefore, a need for genomic information of native and underutilised trees has to be pursued. This effort will definitely aid in documenting and unlocking the large diversity of tree species and help in understanding their evolutionary pattern. Many trees may have limited industrial value. However, these species can be significant in terms of social-cultural beliefs and ecological service. Therefore, the funding agencies should emphasise research based on these grounds to support future needs. With the advent of NGS technologies, it is possible to generate high-quality long-read reference genomes in less time and cost, since trees have complex genomes. Also, these long-read-based techniques will help to acquire précised chromosome-scale contiguity. Recently, the improved genome assembly called 'hybrid assembly' is an advantage over short or long reads, as it has high genome coverage. Advanced tree genome tools can be efficiently applied to refine tree genomic data for precise structural and other functional gene mining for various fast-growing trees. These advanced technologies could be utilised to study species divergence in natural populations and population differentiation through reading nucleotide divergence between populations or at the species level. These genome scanning approaches allow researchers to precisely understand the species differentiation through gene duplication, genetic aberration phenomena. In no time, more emphasis must be given to tree genome research as like microbial and crop genomics. Financial investments should be made to maintain tree genomics resource databases such as Treegenes and Hardwood genomics projects (https://hardwoodgenomics.org/). Since data availability for the research community is paramount to initiate tree genomics-related research. The whole-genome sequencing efforts must be extended to the other trees to understand their genomic architecture, secondary metabolites synthesis, and biomass-related traits to provide profound insights into various candidate genes and gene pathways for functional traits to the economic values of trees. The utilisation of genomic tools from system biology to the tree productivity aspect needs to be emphasised. Thus, the additional avenues beyond the usual areas could be addressed for tree improvement. Finally, tree genomics research must be interdisciplinary, where tree geneticists should work more closely with foresters, physiologists, and bioinformaticians to foster tree genomics research.

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Ecological Niche Modelling and Species Distribution Models (SDMs) in Agroforestry

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Introduction

Ecological Niche modelling (ENM), also known as species distribution modelling (SDM) or habitat suitability modelling, is a computational approach used in ecology, conservation biology, and biogeography to predict the potential geographic distribution or habitat suitability of a species or ecological niche under various environmental conditions. There is a rising opinion that both ENM and SDM vary in certain aspects (Melo-Merino et al., 2020); yet these concepts have been used extensively in the disciplines of ecology, biogeography, and conservation to forecast how a changing climate may affect species. ENM/SDM has also been used to manage invasive species, plan protected areas management, and estimate the effects of climate change in evolutionary biology and ecology. The greater accessibility of digital data, user-friendly software, and instructional resources, as well as the growing interest and focus on these techniques, have supported the development of this field. Recent developments in data analysis and information technology have provided an edge to ecologists and conservationists to use this computational approach to a greater extent.

The origins of this ecological approach can be found in earlier works that connected biological patterns with environmental changes like geographic gradients. Also, the studies that showed how individuals rather than groups responded differently to environmental factors inspired the creation of methods to represent individuals as species. In order to provide a picture of possible distributions of species at the landscape level, ENM/SDM infers correlations between species distributions (as records of occurrence or abundance) and environmental characteristics at selected study sites. These models have also been referred to in the literature as habitat models, climate envelopes, range maps, ecological niche models (ENMs), resource selection functions (RSFs), correlative models, and spatial models.

Among the three important parameters influencing the SDM i.e. (1) data on species, (2) environmental covariates, and (3) a modelling technique. The last parameter plays a crucial role. Typically, the modelling is done at two levels – a) single model algorithm technique and b) ensemble technique. The foundation of ensemble modelling is the idea that each model algorithm exhibits some meaningful "signal" regarding relationships in the real world, as well as some noise brought on by the data and the limitations of the algorithm. As a result, ensemble modelling uses many models to more effectively separate the signal from the noise. Therefore, the choice of algorithm matters and the algorithms are categorised (Rathore and Sharma, 2023) as

- Regression Models - Generalized linear models (GLMs), Generalized additive models (GAMs), Multivariate adaptive regression splines (MARS)
- Classification Models - Flexible discriminant analysis (FDA) and Classification and regression tree (CART)
- Complex Models - Random Forest (RF), The genetic algorithm for rule-set production (GARP), The maximum entropy (MaxENT) method, and Artificial neural network (ANN).

Among these algorithms, one stands as a popular choice for SDM modelling i.e., MaxENT. It is an algorithm for general-purpose machine learning that calculates target probabilities by identifying the distribution that is most entropic (i.e., uniform) while adhering to the requirement that each environmental variable's expected value match its empirical average (i.e., the average value of the variable at a sample of points from species distribution). After the first publication on MaxENT by Phillips et al. (2006) who introduced the MaxENT application as a tool/software based on the maximum entropy method for SDM with presence-only data; there are several publications that have used MaxENT.

Over the period of 23 (2000-2023) years, there were 210 scientific publications published in 103 journals with an annual growth rate of 27.81% in India alone (Figure 1) and the publications peaked in 2013. About 778 authors contributed with an average of 4.79 authors per document and 32.34 % international collaboration for publishing. There were only 3 authors who published single-authored scientific documents which indirectly indicated the level of collaboration among authors in India. Almost all states were covered with at least 5-10 publications, with hotspots of the studies being Karnataka, Kerala, Tamil Nadu (Western and Eastern Ghats), Uttarakhand and Jammu (Himalayan region). The least studied will be the western part of India (arid and semi-arid regions). With regard to the spatial scale, the study area in many of the studies has not been confined to selected regions within the state but even pan-India level studies have also been reported. For instance, the invasion potential of the mango fruit borer (Choudhary et al., 2019), future prediction of *Boswellia serrata* (Rajpoot et al., 2020) and Potential Area for Cultivation of *Melia dubia* (Sundaram et al., 2023) were studied at country level; whereas predicting the potential distribution of *Justicia adhatoda* was carried out at district level (Yang et al., 2013).

It is pertinent to point out that apart from the java based MaxENT software, some of the studies have used in MaxEnt tool in other formats like a plugin in the QGIS, an interface based on GRASS GIS and numerous R packages like dismo, ENMeval, SDMPlay, rmaxent, MIAmaxent, kuenm, ENiRG, maxlike, etc. which is clear indications on the dominance of MaxENT algorithm.

To understand the changes in the MaxENT-based studies based on institutes, keywords and journals over the last two decades, the three-field plot from bibliometrix tools was used. The left side indicates the top 20 institutes in India; the right side indicates the name of journals and the middle field indicates the keywords. Figure 3 provides a bird's eye view of the interlinkage in the published studies between 2000 and 2023. It reveals that ecological informatics, ecological engineering and current science are some of the journals where dedicated research on ENM/SDM based on MaxENT in India is being published. The central segment indicates sides the keywords from the published papers; it is clear that the Western Ghats and Himalayas are two significant regions where SDM-based studies are being carried out.

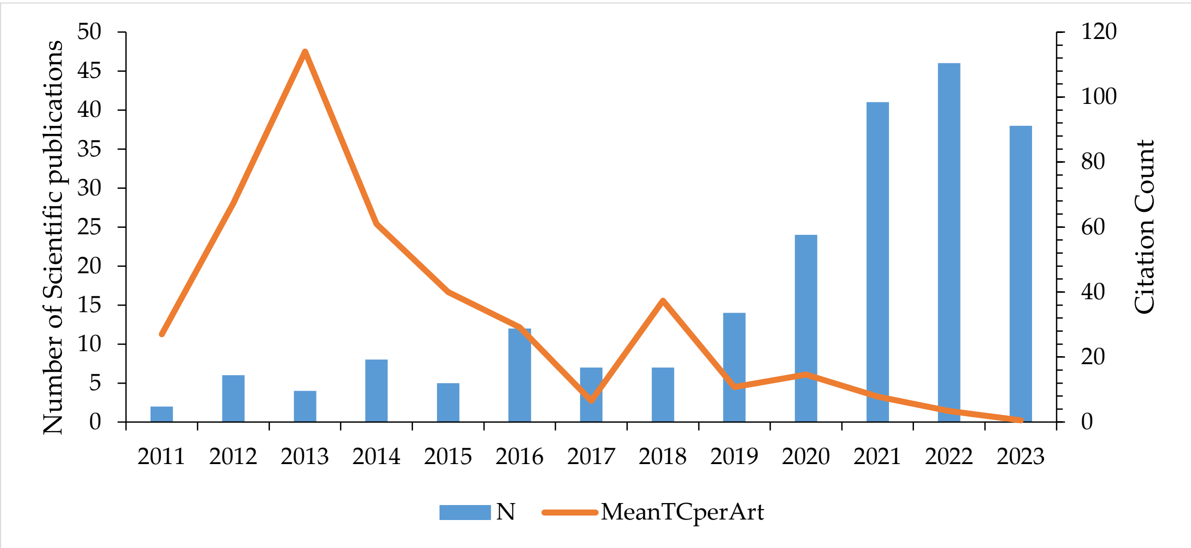

Figure 1. Scientific publications based on MaxENT over the years across timescale

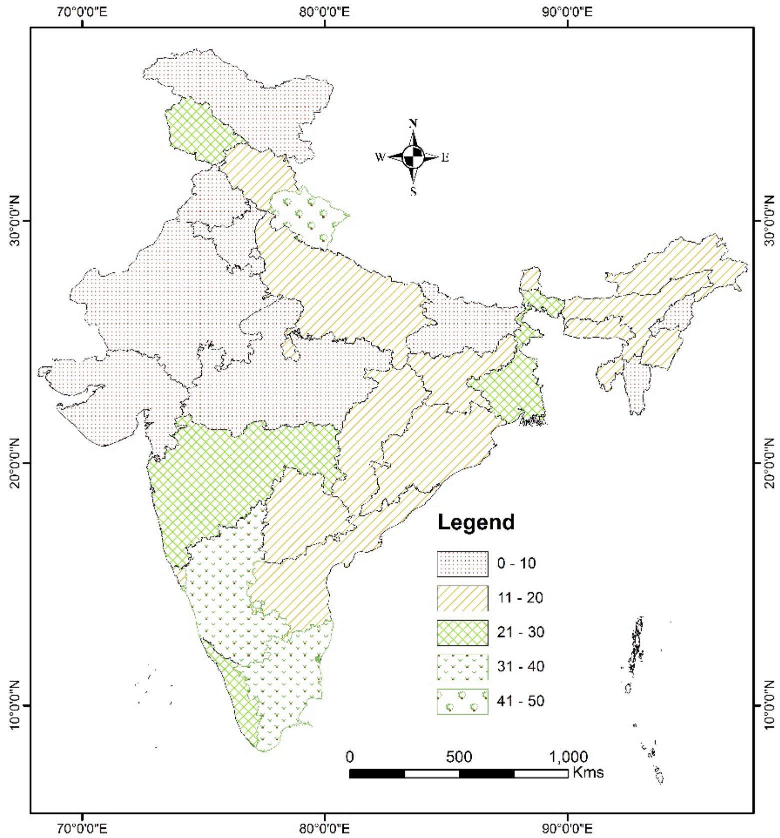

Figure 2. Scientific publications based on MaxENT over the years in India

To understand the different aspects where MaxENT has been used, the publications were sorted out on the thematic study subjects (Figure 3). SDM modelling was widely used to study trees, herbs and mammals in the Indian context. More peculiarly, the MaxENT tool has been also used for some landscape-level studies. For instance, Pandey et al. (2020) assessed the landslide susceptibility along riven models along the Tipari to Ghuttu highway corridors in the Garhwal Himalaya by coupling MaxENT output with DEM, NDVI, Slope, Aspect and drainage density datasets. Unlike SDM models for flora or fauna where the presence locations of the species of interest are deployed along with environmental parameters such as temperature and rainfall, the studies on landscape (Pandey et al., 2020), forest fire prediction (Banerjee, 2021), transition in lagoon ecosystem (Santhanam et al., 2022), etc. are some of the new methodology by tuning the MaxENT Tool with additional remote sensing & GIS datasets to meet the desired objectives. It is pertinent to point out that all of the studies were carried out after 2020 which indicates that new horizons using MaxENT are being explored and there will be more publications, as indicated by Lotka's law. All studies focus on the fundamental principle i.e., the MaxENT model/tool is based on theory of statistical mechanics and information concept which gives an approximation of a likelihood phenomenon based on known events.

Recently, Rathore and Sharma (2023) reported that SDM can be utilised for Forecasting, Restoration planning, Climate change effect assessment, Critical Habitat Identification, Fishing Zone Identification, Pollinator range prediction, Disease spread prediction, Fire regime, Corridor identification, Conservation Status prediction, Conservation Planning, Habitat range shift prediction, Protected Area management, Hotspot identification and Invasive species range identification, etc. Our results indicate that MaxENT can be used in many other areas and it is up to the researchers to apply the tool. More specifically, the category 'Others' mentioned in Figure 4. which are based on the application of the MaxENT tool for gully erosion and land subsistence susceptibility mapping, predicting the expansion of dengue vectors, predicating the monkey fever risk, assessing the impact of overuse of groundwater for agriculture and many other works using MaxENT Tool.

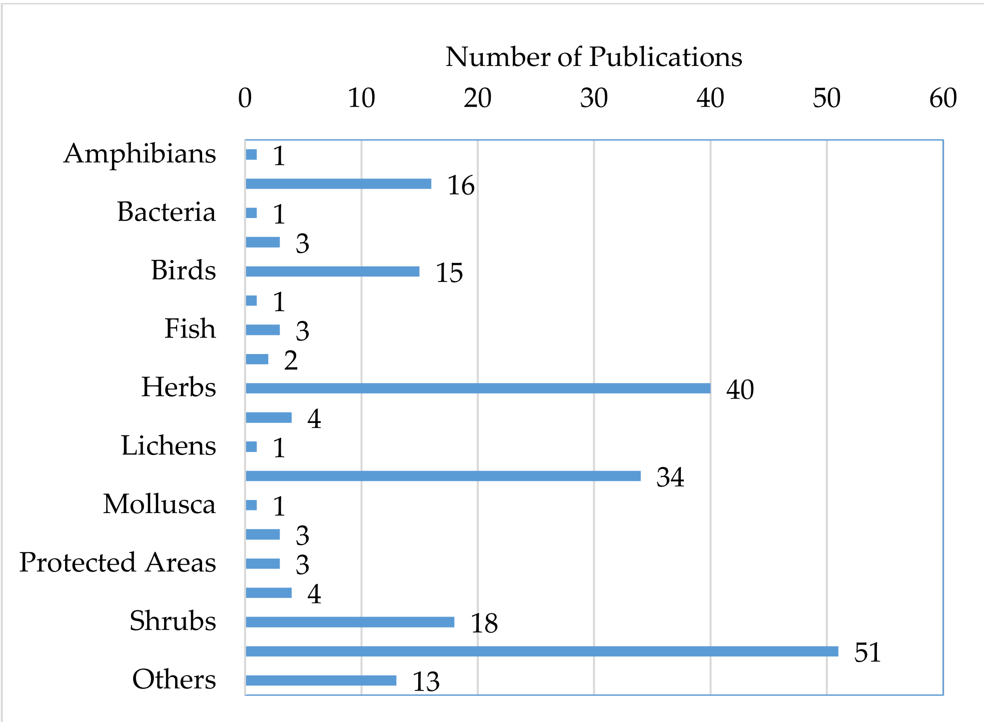

Figure 3. Different thematic groups and their corresponding number of publications between 2000-2023.

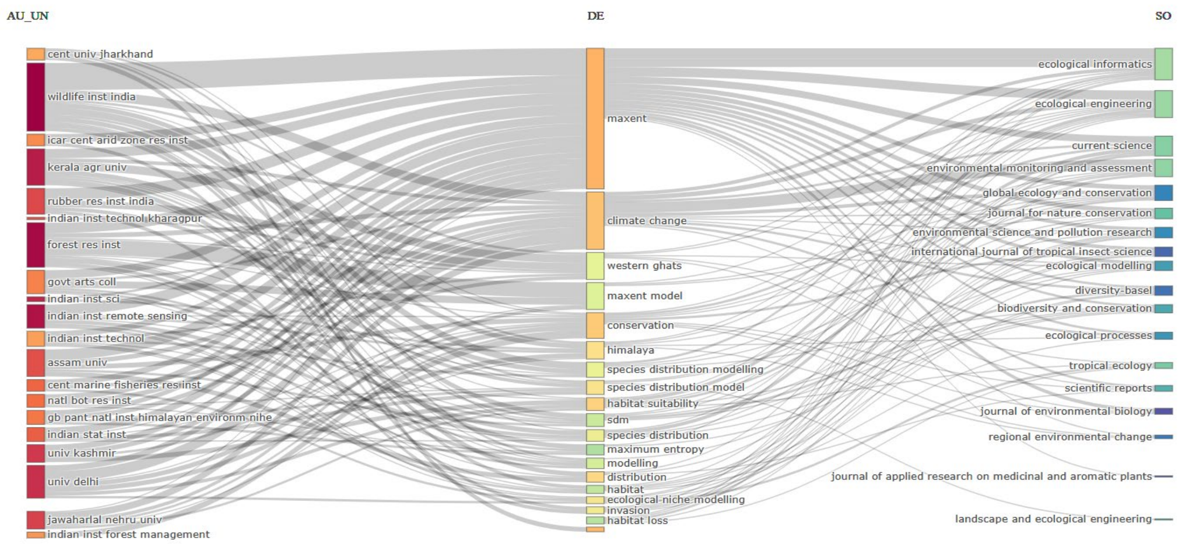

Figure 4. Three-field plot depicting linkage of the top 20 institutes, keywords and journals for MaxENT-based studies 2000-2023.

All these studies show that this Java-based software has aided in the application of information theory and related statistical concepts for predicting factors. The use of presence/occurrence-only data (both for continuous and categorical data) has been regarded as one of the MaxENT tool limitations. However, Jha et al. (2022) have proved that MaxENT performs better than occupancy models which use both presence and absence data.

All the research works have invariably used bioclimatic data from the worldclim (https://www.worldclim.org/data/worldclim21.html) apart from additional datasets like altitude, Digital Elevation Model, NDVI, Enhanced Vegetation Index, Landsurface Temperature, Landuse and landcover, Compounded Topographic Index, Forest Type map and Forest Cover map, Direct Normal Irradiance, evapotranspiration, fraction of absorbed photosynthetically active radiation, water vapor, Leaf Area Index, Ozone, NOx, albedo, aerosol absorbing index, biodiversity indices, hill shade, habitat heterogeneity index, distance from road, soil properties, flow accumulation, Ivlev's index of selection and even human footprint have also been used. All these indicate the flexibility and wider application of MaxENT tools for identifying the niche and distribution of the species in present as well as future climatic conditions. However, the datasets are mostly open-accessible or generated for the particular study site and the inference generated directly depends on the number of occurrences datapoints used. Studies from the Indian context, are primarily accessed from databases like GBIF, Ebird Atlas or data points generated from the field survey. One particular aspect is the range of occurrence datapoints which can range from ~30 to 3500 as indicated in Figure 5. It is pertinent to point out that there are few studies with more than 3500 occurrence points which are not included here in the figure. For instance, a study assessing the impact of climate change on the 10 hornbill species had about 93184 points total from GBIF, however only 5055 points were included for modelling to avoid bias and cluttering (Sarkar and Talukdar, 2023). There are certain taxa such as the Mollusca where the published studies supplement the field survey datasets and therefore mentioning the GPS coordinates in the study reports/publications will be useful in a larger context (Bharti and Shanker, 2021).

Relevance of ENM in Agroforestry

Agroforestry as a land-use practice is very much relevant to United Nations' Sustainable Development Goals (SDGs) and it potentially addresses 12 out of 17 SDGs (Arunachalam and Ramanan, 2021). In most developing countries like India where land is a scarce resource, a large proportion of land cannot be diverted for tree plantation and forestry practices. In this context, agroforestry is a very much viable option for meeting the increasing wood demand and also meeting the 33% green cover target of FAO (Joshi et al., 2011). Owing to its importance, India adopted the first agroforestry policy in 2014 (Ahmad et al., 2019). Reviewing the tree plantations and agroforestry practices in the country, few industrially important tree species such as Eucalyptus, Casuarina and Populus got the major share owing to the demand from plywood and paper industries (Kulkarni, 2013; Parthiban et al., 2019). Due efforts were made to find alternative species like Leucaena, Gmelina etc. However, these efforts could not gain momentum in replacing the industrial tree species. Moreover, even the very fast-growing bamboo species could not replace the industrially valued species because of many reasons like low pulp recovery, high silica content, etc. (Wang et al., 2021). Further, industrial species like Eucalyptus had also got into controversial clout of high water usage and groundwater depletion (Morris et al., 2004; Reichert et al., 2021). This warranted a need to find an alternative tree species. *Melia dubia* Cav. belongs to the Meliaceae family and is one of the native fast-growing tree species with clear bole and recommended to be promoted as one of the viablchoicesce for plantations and agroforestry (Chavan et al., 2022; Handa et al., 2020).

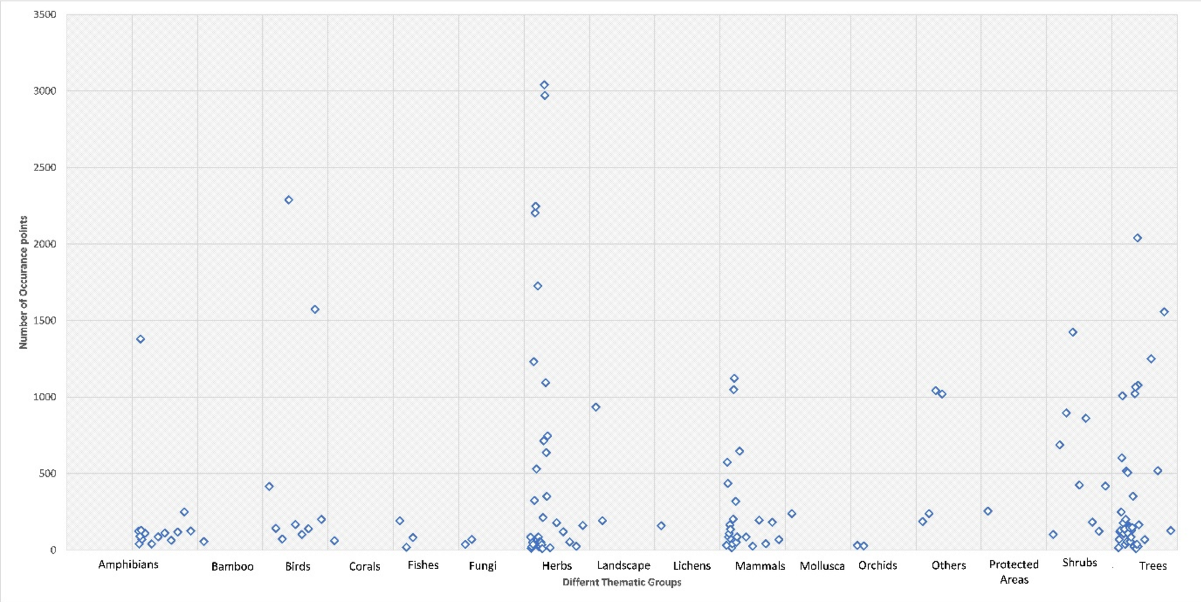

Figure 5. Overview of occurrence data points used for Indian studies

Typically, Meliaceae can be regarded as the timber family, given that important timber species like *Azadirachta indica* A. Juss., *Cedrela odorata* L., *Toona ciliata* M. Roem. and *Swietenia macrophylla* King. belong to this family (Gupta et al., 2019). An overview of the timber supply and demand statistics indicated India as a net importer of wood. Despite having an area of 7,121,249 km2 (21. 67% of the total geographical area), India is a net importer owing to the ban on green felling inside natural forests as well as the policy framed to protect the rich biodiversity for future generations. Thus, the country's wood and timber demand aremainly met by the trees outside forests (TOFs) along with the wood imported from other countries. As per the report released by the Centre for Science and Environment under the theme 'Wood is Good: But, is India doing enough to meet its present and future needs?', TOFs provide the major portion of wood and timber demand. To quote the exact wordings "In India, TOFs is defined as 'all trees growing outside recorded forest areas. TOF provides the meat of India's timber needs, and agroforestry and farm forestry are the backbones of TOF"(Shrivastava and Saxena, 2017). India became a leading example by adopting the National Agroforestry Policy in 2014, a first of its kind. One of the major goals of the policy was "Meeting the ever-increasing demand of timber, food, fuel, fodder, fertilizer, fibre, and other agroforestry products; conserving the natural resources and forest; protecting the environment & providing environmental security, and increasing the forest/tree cover, there is a need to increase the availability of these from outside the natural forests"(GoI, 2014).

Melia dubia as an agroforestry tree species can address various SDGs like no poverty (SDG1) by increasing farmer's income, gender equity (SDG-5) by providing womenfolk fuelwood for cooking, affordable and clean energy/sustainable energy solutions (SDG-7) wood fuel supply to the poor farmers, responsible consumption and production, to ecological footprints (SDG-12) (Arunachalam and Ramanan, 2021; van Noordwijk et al., 2018). Thus, this species has been promoted in different parts of the country (Kumar and Joshi, 2021). In Kerala, this species has been cultivated on large scale compared to commercial crops like rubber (Binu, 2019). Furthermore, there are clones/varieties released for this species at the country level. However, it is reported that this species is native to the Western Ghats and therefore, it will be significant to delimit the niche of this species; thereby delineating the areas where this species can be promoted for cultivation.

Ecological Niche Modelling (ENM) aids in modelling and demarcation of the distribution range of the species concerned while also predicting its stable habitats suited climatically under multiple projected climatic scenarios (Adhikari et al., 2019, 2018). Rajpoot et al. (2020) carried out niche modelling for *Boswellia serrata* Roxb. and reported that there is a potential chance for a decrease in the spread of the species in its natural distributions. Thus, recommending a long-term action plan for the conservation of this species. This sort of finding on the conservation of species based on niche modelling has been done for many floral and faunal species (Majumdar et al., 2019; Mipun et al., 2019; Pradhan et al., 2020).

After 1970s, agroforestry gained momentum as a scientific discipline (Nair et al., 2021). The definition of agroforestry clearly states it as a sustainable land-use practice where woody perennials/ trees are grown along with crops and animals in spatial and temporal sequences (Arunachalam et al., 2021). Inherently, farm forestry and agroforestry promote the cultivation of trees in private/farmlands i.e. Trees Outside Forests. The success of agroforestry and farm forestry is highly dependent on the choice of species and thus ENM can play a significant role in pointing out the suitable area for a particular species. A study in Yunnan province has applied ENM for identifying the climate space or niche of ten tree species, and predicted the impact of climate change on the distribution of these species (Ranjitkar et al., 2016). Similarly, ENM based on the BiodiversityR package was used to delineate the "always-suitable" distributions of the *Xanthoceras sorbifolium* Bunge. in China (Wang et al., 2017). In Nepal, the potential zone for Himalayan alder species was delineated using MaxEnt and insisted that only 24% area of Nepal is suitable for *Alnus nepalensis*. All these studies have attempted to provide practical solutions to one of the fundamental issues faced in agroforestry: selecting a tree/ woody perennial species so that it is suitable for that region.

The museums, herbariums and institutional collections have been reported as sources for occurrence data points and there is a need to bring these occurrence datasets into a common platform. Given that many of the environmental predictors and other predictors are available in open-access platforms, ensuring the easy accessibility of the dataset will pave robust application of ENM/SDM in real-time decision-making. Relying on a single dataset might be a regarded as limitation of this study. However, this work provides an overview as well as insight for beginners on ENM/SDM.

Acknowledgement

The entire content is prepared for the Winter School on Agroforestry Innovations for Climate-Resilient Development, Transformative Land Use, and Livelihood Security during 14–23 November 2025, sponsored by the U.P. Council of Agricultural Research. It is based on the publications of Dr. Suresh Ramanan S and his co-authors whose contributions are acknowledged here also.

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Harnessing the Productive Potential of Degraded Lands through Hortipastoral Systems

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Abstract

Under rainfed condition, monocropping is always full of risk due to erratic nature of rainfall. Under such situation diversified agriculture including animal husbandry along with incorporation of suitable fruit species in farming system is advocated to reduce risk along with sustain productivity and livelihood improvement with natural resource conservation. Under rainfed condition animal husbandry has been proved to be one of the most suitable secondary occupations for small, marginal and medium farmers. In the animal husbandry about 65-75 % expenditure is incurred on feeds and fodder. In our country, there is a deficit of 62-65 % green fodder and 22-25 % dry fodder and 35 % fruit/head/day of requirement. If above facts are taken into considerations along with increasing population of animals and human beings and decreasing area under forest, grassland and fodder crop, no doubt hortipastoral system with animal husbandry will be one of the most economical, socially accepted and eco-friendly system to mitigate the gap between demand and supply of food, fodder and fuel wood up to some extent and secured livelihood.

Introduction

In India out of 329 m ha geographical area total 142 m hectare of arable land 97 m ha (70 %) is rainfed which comes under arid and semi-arid zone. In these areas crop husbandry is a big gamble due to uncertain rainfall. Under such situation incorporating of fruit trees along with animal husbandry in common farming system is advisable to improve lively hood security and economic stability of people. In India 16% of human population of world has to sustain on only 2.33 % of total geographical area. Due to increasing population pressure, utilization of degraded lands or rainfed land is essential to feed nutritious diet with protective food (fruit). Similarly, our country is the largest livestock holder in the world and support 55% of its buffaloes, 16 % of the cattle, 20 % of the goats and some 4% of the sheep. These scenario of demographic pressure exert pressure on available land most of which is used for arable farming and food production. The pressure is bound to increase in future. Only 8.33 million ha of the total cropped area of the country is under forage crops and there is very little scope for increasing area under forage due to pressure on land for food and commercial crops. A recent estimate indicates that the deficiency in total forages need is about 68 per cent of green fodder and about 53 per cent of dry forage. This deficit is likely to increase further as (i) the area under forage crop is declining because of growing cereal and other cash crops to meet the increasing pressure of population growth, (ii) the animal population is increasing every year by almost 2 per cent (iii) cultivable land is decreasing due to urbanization and industrial growth and (iv) forages in future are going to have competition from liquid fuel shortage. The solution therefore, lies in maximizing forage production in space and time, through integration of forage crops in established or grown-up plantations as well as establishing orchard.

Hortipastoral system

Integration of fruit trees with pasture (grasses and or legumes) in the same unit of land. This system acts as one of the best and economic alternative system for class V and VI (Singh, 1996). It can supply the protective food (fruit) for human being and fodder for animal and thus help in bridging the wide gap between the supply and demand of fruit and fodder. However, the success of developing hortipasture land use system depends largely on selection of fruit plants. The selection depends upon objectives besides soil and climate.

Establishment of Horti- pastoral System

Protection of area from Animals

The area should be protected from biotic interferences. This may be done with any fencing material as per its availability such as barbed/woven/chicken wire with angle iron/stone wooden pole, cattle proof trenches (2x1x0.3 m), live hedge fencing etc.

Soil and water conservation through water harvesting *in- situ*

Water is always a critical factor in rain fed situation. Survival can be generally enhanced by reducing runoff and collects at the root zone by any conventional practices of soil and water conservation.

Selection of suitable fruit tree

Selection of fruit tree for horti-pastoral system under semi-arid/rain fed environment is quite difficult task. Prior to selection of fruit species, it is pre-requisite to select a particular variety for that region. The tree should be chosen which are complementary or less competitive for understorey pastures. In continuous garaging system, custard apple could be an ideal option as it is not browsed by live stock and hardy too. Fruit like ber will grow very well in combination with pasture, as the foliage is very notorious and palatable. Suitable fruit species with suitable varieties for degraded land/rainfed situation given in Table 1.

Selection of suitable perennial grasses

For specific agro climatic condition it is also important for increasing forage as well as animal productivity through sustaining productivity and balancing fodder value. For different agro-climatic conditions, suitable species of pasture for horti-pastoral are given in Table 2.

Establishment of fruit tree in hortipasture system

After protection and selection of suitable species, planting and sowing may be done during monsoon season. For fruit trees pit size 1x1x1m should be prepared at 6-10m apart depending upon fruit trees species before onset of monsoon The pits should be filled with well rotten FYM (30-50 %) of the total volume of the pits) and good soil along with termicide. In between row of fruit trees transplanting / sowing of grasses and legume should be done in 1:1ratio at 50 cm spacing. In sodic soil use of 3 kg gypsum + 8 kg FYM or 30 kg sand + 30 kg FYM along with original soil has showed promising results. Apart from FYM or compost, paddy husk, groundnut shell, green leaves of *neem* or any other trees could also be used as filling mixture. Chemical fertilizer generally recommended are DAP, Single super phosphate with urea. Small amount (50 g) of BHC/ Aldrin 10% dust may be applied in light textured soils to prevent termite attack. Water holding capacity in pits improves with the amount of FYM/ compost added and it should occupy minimum 25 % volume. Water holding capacity may be further improved by filling bentomite clay or tank silt (5 cm thick layer) at the bottom which will check the deep percolation losses. In order to get higher forage production from pasture species 30 kg N + 20 kg P_2O_5 /ha /year should be given during monsoon season.

Establishment Techniques of grass: A moderately good tilth seedbed is required for better establishment of pastures and must be sown at the beginning of the rainy season on a drizzling day. Seeds could be broadcasted, since the seed is small in size, seeding at shallow depth is important. However, raking of the soil after the broadcasting improves the germination considerably; this may be done by running a brush wood (branch with twigs) over the area. For larger areas broad casting of seed pallets (seed and soil) are also recommended. In hortipastoral system pasture establishment are recommended through transplanting of rooted sleep or root tussock along with legume row in 1:1.

At Indian Grassland and fodder Research Institute, Jhansi (U.P.) experiments on production potential of hortipastoral systems were conducted from last twenty years given as under.

In *Ber*. based hortipastoral system during first phase (1990- 98) involving various combination of *C. ciliaris*, *S hamata* with jujube (*Ziziphus mauritiana* L.) cv. Gola planted at 6 m x 6 m. The ber started producing fruits from third year on wards. Initially, the fruit production was nominal which increased from 5.48 to 7.6t/ha The pasture production showed an increased trend during the initial three years and forage production was in range of 4-5 t DM/ha.

In 2nd phase of experiment (1999-2000) *ber* tree were utilized for bajara fodder production with pruning management of main trunk. Same orchard produced 20-24.2 t green fodder / year along with 8.2 -14 t /ha fruit every year.
In 3rd phase of experiment (2001-06), the ber trees with secondary branches pruning with different pasture combination viz., Guinea grass +*S. hamata*, Dinanath grass +*S. hamata*, Guinea grass +Dinanath grass +*S. hamata*. The medium pruned tree produced significantly higher ber fruit yield (7.3t/ha) as compared to severe (5.07 t/ ha) and light pruned tree (6.5 t/ha) Among pasture combination under grown up ber orchard Guinea grass +*Stylosanthes hamata* produced significantly higher yield (6.29 t DM / ha) followed by Guinea grass + Dinanath grass + *Stylosanthes hamata* (4.68 t DM / ha) , Dinanath grass + *Stylosanthes hamata* (2.82 t DM / ha) and natural biomass(1.26 t DM/ ha).

In 4th phase same orchard rejuvenated through micronutrient foliar sprays and bunding along with guinea grass + *S. hamata*. Bunded plot gave significantly higher pasture yield (7.41 t DM/ha) as compared to without bunded plot (6.05 t DM//ha). Two foliar sprays of Borax (0.3-0.6 %) and Zinc Sulphate (0.2% - 0.4%) significantly increased fruit yield (6.78 t/ha) over control (4.82). Over all bunded plot produced higher yield (6.49 t/ha) at par with without bunded plot (6.28 t/ha).

Aonla (cv.NA-7) base hortipastoral system (1996-06) involving aonla tree planted at 6 m x 6m in 9 plants / plot (18m x 18m), *Dichanthium annulatum* and three nitrogen doses. The pasture production in association with tree was higher (3.38t DM/ha) as compared to pure pasture (3.07t DM/ha). The fruit production was started from 5th year of planting and over the six years of production produced 8.6-9.5 t fruit/year. In 2nd phase (2006-09) same aonla orchard intercropped with guinea grass and slylo. Maximum fruit production (14.9 t/ha) was recorded with Stylo intercropping. Pasture production was higher in association with tree (3.4 t DM/ha) as compared to sole pasture (3.0 t DM/ha). Guinea grass + *S. hamata* gave maximum forage (4.05 t DM/ha) as compared to sole guinea (3.85 t DM/ha) or sole *Stylo* (2.05t DM/ha). In the third year very poor persistency of stylo was noticed with guinea.

Guava (Cv. Lalit and Shweta) based hortipasture system was established in 2007-8 with soil and moisture conservation practices. In the first year of pasture establishment, sole pasture produced maximum (4.7 t DM/ha) as compared with intercropped pasture (4.6 t DM/ha). In the third year of plantation, it started fruiting. The cultivtar Lalit produced maximum fruit 2.84 t ha as compare to Shweta (2.3 t/ha). Fodder productin ranged fron6.62-8.35 t DM/ha. Similarly, aonla based hortipastoral system established in 2007 with different soil nad water conservation techniques. In the 1st year only *S. seabrana* was sown that produced 0.7-0.9 t DM/ha. In the second-year staggered contour trenches recorded significantly higher pasture production (4.70 t DM/ha) ie.62-65 % higher over control. The contribution of grass and legume component in total pasture production was 63-67 percent and 35-37 percent respectively in different treatments.

Subramanian, *et al* (2006) reported that growing of Napier bajra grass cv.Co.3 coulld be successfully grown in the interspaces of coconut is possible by improving physico- chemical properties of soil. They were used coconut waste 14-16 t /ha/yr in the trench made between the coconut interspaces and planting Napier bajra Co 3. They were reported from one h of coconut garden around 100 tonnes of green fodeer can be harvested which will be sufficient to maintain 8-10 milch animal. Ahamad *et a*l (2006) also reported that high humid northeastern part of country where coconut is not traditional but adopting easily. The inter space of bearing coconut orchard may be successfully utilized for growing of rice nursery during kharif and fodder mainly, sorghum, maize and oat in rabi with increasing yield of coconut. Similarly, Shinde *et al* (2006) also reported from Maharastra that Cashewnut plantation understorey could be utilized for growing of perennial pasture.

Advantages of Hortipastoral system

Fruit demand/ supply, area and production:

India's share in the world fruit production is 10 % fruit crops occupy an area of about 3.8 million ha (about 2.07 % of total [190m ha] Agriculture land) with an annual production of about 45.5 million tones of different fruits that supplies only 46% of the country (Ganeshmurthy *et. al.* 2004). There is gap of 35 percent in fruit demand and suppy. This gap could be minimized by utilizing of degradedland with suitable species of fruit. Hortipastoral system provides 5-15 t fruit/ha/year depending upon fruit species.

Fodder demand and supply:

Horti- pastoral system can supply fodder to farmer by two ways. First fom valuable leaf as top feed. These leaves form nutritive fodder for cattle eg. ber 8.6%, *bael* 15.1%, *gonda* 15.1%, *mahua* 15%, *khirni* 9.5%, *jamun* 8.8% & *jharber* with 11.5% crude protein (Tejwani 1994) provide palatable forage to animal. Similarly, fodder tree provides palatable and nutritive fodder in lean period through lopping management. Secondly, the pasture grown in combination with fruit trees supplies the herbage to animal

Fuel wood/ Energy from Biomass: Fuel wood/ Energy from Biomass:

The forest survey of India estimated that in 1987, the consumption of fuel wood was 157 million tones (235 million cu.m.), while its production was only 40 million cu.m. There was thus, a shortfall of 195 million cu.m. Such shortfall is a major cause of deforestation. In the developing countries, 3 x10^{9} tones fuelwood is burnt every year (Pimental *et al*, 1994). More than one half of the people who depend on fuel wood have inadequate supplies. FAO estimated that the poor spend 15-25% of their income for fuel. For both cooking and heating 912-1200 kg/year wood is required /person (Apasamy, 1993). Fuel wood for cooking and heating may cost almost as much as food requires a substantial amount of time and effort. For example, in India and other developing countries families spend from 1.5 to 5 hours each day collecting biomass to use as fuel (Peskin *et al*, 1992). The few fruits, like ber, phalsa & grape etc. required light to sever pruning and supplied fuel wood.

Soil Improvement:

Significant improvement in soil physical and nutrient attributes was observed through hortipastoral system. Kumar and Chaubey (2008) reported that after 10 years of land use under aonla-based hortipastoral system the improvement in organic carbon (about 92 %), available N (20.8%), P (9.0%) and K (58%) were higher in hortipastoral plots compared with the sown pure pasture (organic carbon 68 %, available N 5.06 %, P 0.8 % and K 38.6%).

Economic stability:

Involvement of fruit trees in farming system reduces risk (Dayal et al., 1996). Korwar et al (1988) reported that the fruit trees are very hardy, deep rooted and tolerant to abnormal monsoon e.g. early or late onset, intermittent dry spell, early withdrawal, uneven distribution of rainfall etc. better than short duration field crops. The fruit viz; aonla, bael, Custard apple, ber, pomegranate, guava, jamun, gonda, etc. can be grown successfully in semi-arid condition (Vashishtha, 1991). Farmers of semiarid region of central India got, approximate net profit by growing ber Rs. 25,000/ha, Aonla 60,000/ha custard apple 20,000/ha can get easily (Kumar et al 2001). Kumar and Chaubey (2008) also reported that the B: C ratio over 10 years of experiment for pure pasture was 1:1.85, whereas in association of aonla tree it was 1: 3.70. In the same orchard intercropping of guinea grass + Stylosanthes hamta gaeve B:C ratio (1:6.24). Kumar and Ram (2009) reported the economics of the system (Table 3) showed that pruning intensities and understorey pasture combinations influenced the benefit:cost ratio of 10-year-old ber plantations. The maximum B: C ratio over four years of experiment was recorded when trees were pruned medium (1: 3.99) followed by light (1: 3.69) and severely pruned trees (1: 2.65). Among understorey pasture combinations, guinea grass with stylo gave maximum B: C ratio (1: 1.99) followed by guinea grass + Dinanath grass + stylo (1:1.66), Dinanath + stylo (1: 1.19) and natural vegetation (1: 1.10).Guinea grass is perennial where as Dinanath grass is an annual comes every year by self-seeding.In first year low natural biomass was recorded due to land preparation and other operations followed for tree and pasture sowing. In the subsequent seasons, the production was influenced by rainfall. It can be concluded that maximum profit from 10-year-old ber cv. Gola plantation can be obtained by medium pruning with understorey pasture of guinea grass + *S. hamata*.

Employment Generation: The employment generation by growing wheat and maize is only 143-man days/ha/year; whereas, the fruit crops such as mango, grapes and papaya generate 800-, 2500- and 350-man day/year respectively. Moreover, employment generation in cereal crops is seasonal, whereas, there is no lean period in horticultural crops (Sandhu *et.al*. 2000). Kumar and Chaubey (2008) reported that incorporating aonla tree in sown pasture of *Dichanthium annulatum* (2.07-man days per month) the employment generation could be increased from 2.07/month to more than double (4.15 /month) because a number of operations increased in orchard from time to time for establishment, plant protection, harvesting and collection of fruit along with grass harvesting and other operations.

Ecological balance

Hortipastoral system restore ecological balance by greening semi-arid/ dryland through mixture of fruit trees and pasture (grass+ legume) for the persistence and productivity under shaded or low radiation situation (Hazara,1994). This system checks further land degradation improves the carrying capacity of native grasslands and conserves the soil. Pareek (1993) noted that fruit trees like tamarind in pastoral system should be able to fix nitrogen in soil.

Management of fruit trees in hortipastoral system

The success of a hortipastoral model depends largely on efficient management of each of its components to give optimum performance. Major factors for success of fruit crops in hortipastoral models are related to establishment of young plants, their proper training and pruning, optimum nutrition, protection from adverse agro-climate, disease and insect pest. For protection from water stress and intense radiation, mulching of basin should be done from April to June. The damage by pest, disease and animals affects establishment of the young plants. Planting is done in pits ($1m^3$) which are filled with manurial mixture and termicide to protect from termite. Depending on location, planting can be done on contour, terrace, trenches, gullies or at lower ends of micro-catchments for effective accumulation of run off to provide optimum moisture condition in the root system. Shading to protect from intensive radiation may be required particularly in south India whereas, in north India, protection from cold during winter is important. Drip irrigation has been found successful in dry degraded lands to supply moisture to Kinnow plants under hortipastoral system.

Table 1. Suitable fruit crops and cultivars for different rainfall zones.

Rainfall (mm) zone	**Fruit crop**		**Cultivars**
Less than 350	**Common name**	**Botanical name**	
	Ber	*Z. mauritiana*	Seb, Gola, Mundia
	Gonda	*Cordia myxa*	Local strain
	Ker	*Capparia decidua*	Local strain
	Pilu	*Salvadora oleoides*	Local strain
350-500	Ber	*Zizyphus mauritiana*	Katha, Maharwali, Bagwadi, Seb, Gola, Mundia
	Aonla	*Emblica officinalis*	Banarasi, Hathijhool, Chakaiya,
	Khirni	*M. hexandra*	Local strains
	Jamun	*Syzygium cuminii*	Local strains
	Mul*berry*	*Morus alba*	Local strains
500-700	Bael	*Aegle marmelos*	Faizabad selection, N.B.5, N.B 9, CISH2

	Mango	*Mangifera indica*	Seedlings
	Custard apple	*Annona squamosa*	Balanagar, Mammoth, Washington
	Sour lime	*Citrus aurantifolia*	Baramasi
	Aonla	*Emblica officinalis*	Baramasi NA 7, NA 6, Krishna, Kanchan
More than 700	Mango	*Mangifera indica*	Bombay green, Chausa, Safeda, and local cultivar
	Pomegranate	*Punica granatum*	Jalor seedless, Jodhpur red
	Guava	*Psidium guajava*	Allahabad Safeda, L-49
	Jackfruit	*A. heterophyllus)*	Local strain
	Wood apple	*Limonia acidissima*	Local strain
	Tamarind	*Tamarindus indica*	Local strain
	Aonla	*Emblica officinalis*	NA 6, NA 7, Kanchan, Chakaiya.

Source: Kumar and Kumar 2001

Table 2. Suitable pasture species for drylands

Rainfall (mm) zone	**Grass/ Legume Name**	**Soil type**	**Dry forage yield (t/ha)**
Less than 350	Buffel grass (*Cenchrus ciliaris*)	Sandy to sandy loam	4.0
	Bird wood grass (*C. setigerus*)	Sandy to sandy loam	3.0
	Sain (*Sehima nervosum*	Red, gravelly to sandy loam	2.5
	Stylo *(Stylosanthes scabra)*	*Sandy to sandy loam*	*2.5*
	Butterfly pea *(Clitoria ternatea)*	*Sandy loam to Silty clay loam*	*3.0*
	Bankulthi *(A. scarabaeoides)*	*Gravelly, sandy loam well drained*	*2.0*
350 - 500	Blue panic (*Panicum antidolate*)	Loam to sandy loam	3.0
	Marvel	Loamy to clay loam	2.5

	(*Dichanthium nnulatum*)		
	Dinanath grass (*P. pedicellatum*)	Loamy to clayey loam	3.0
	Bahia grass (*P. notatum*)	light	3.5
	Sabi grass (*U. mosmabicensis*)	Sandy to sandy loam	3.0
	Stylo *(Stylosanthes hamata)*	Sandy loam to loam	3.5
500-700	Rhodes grass *(Chloris gayana)*	Sodic, loam to sandy loam	2.5
	Stylo *(Stylosanthes hamata)*	Sandy loam to loam	3.5
	Siratro *(M. atropurpureum)*	Sandy to sandy loam	1.8
More than 700	Napier grass (*P. purpureum*)	sandy loam to clay loam	4.0
	Marvel (*Dichanthium nnulatum*)	Loamy to clay loam	2.5

Source: Korwar et al,1988

Conclusion: Based on above discussions, through the development of hortipastoral system in degraded land of India particularly under rainfed situation we can make possibility of imparting stability to farmer's income by promoting integration of fruit trees in their farming system as well as animal husbandry occupation. Hortipastoral systems provide nutritional security through fruit as well as animal product, maximize biomass productivity and sustained productivity.

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Drones and Remote Sensing in Agroforestry: Applications, Advantages, Challenges, and Prospects

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Abstract

Agroforestry offers numerous advantages for biodiversity, soil health, carbon sequestration, and sustainable land use by integrating trees, crops, and occasionally livestock into a single land management system. The mapping, monitoring, and administration of agroforestry systems have been completely transformed by developments in drone technology and remote sensing. This paper summarises the fundamentals of drones and remote sensing, examines their primary uses in agroforestry, offers a few case studies, talks about the important issues, and predicts future developments in this quickly developing sector.

Introduction

Agroforestry is a land-use system that creates intricate ecological and economic relationships by combining crops, sometimes animals, and woody perennials like trees or shrubs on the same plot. By sequestering carbon, this integrated strategy promotes soil health, increases biodiversity, and helps mitigate climate change. Recent developments in drone and remote sensing (RS) technology have improved the efficiency and precision of mapping and monitoring these dynamic systems, which are crucial for informed management and policy planning (Chang et al., 2025; Ram & Arunachalam, 2024).

From manual surveys to advanced methods including remote sensing, Geographic Information Systems (GIS), and Unmanned Aerial Vehicles (UAVs, or drones), mapping in agroforestry has changed throughout time. Using reflected or transmitted electromagnetic energy, remote sensing collects information about things or landscapes without making physical contact. GIS integration enables the interpretation, display, and analysis of spatial data for decision assistance. By overcoming the drawbacks of satellites (cloud cover, revisit frequency) and ground surveys (labour, access), drones offer a unique ability to gather ultra-high-resolution spatial data. Drone, satellite, and ground data are then combined using GIS platforms for ecological monitoring, land-use planning, and site selection (Devi et al., 2025).

RS GIS and Drone Technologies, Sensors, and Data Workflows

The study of gathering data on objects or regions from a distance, usually using sensors installed on satellites or aerial vehicles like drones, is known as remote sensing (RS). RS allows for continuous multi-temporal monitoring of land cover and land use by capturing reflected or emitted electromagnetic energy from the Earth's surface to evaluate properties including vegetation, soil, and water (Ahmad et al., 2022). Geographically referenced data can be captured, stored, analysed, managed, and displayed using a Geographic Information System (GIS), which combines hardware, software, and data. By viewing, interpreting, and visualizing data in a variety of formats, including maps, charts, and spatial reports, GIS enables researchers and land managers to identify patterns, linkages, and trends that are essential for making sustainable decisions in agroforestry (Khaliq, 2014; Ram & Arunachalam, 2024). Raw sensor data is transformed into useful spatial knowledge by the combined influence of RS and GIS. RSGIS makes it possible to precisely map, monitor, and manage agroforestry systems by fusing high-resolution images (from drones, satellites, and airborne sensors) with GIS's potent spatial analysis tools. Applications include soil mapping, biodiversity monitoring, land-use change detection, vegetation health evaluation, and site appropriateness analysis (Ahmad et al., 2022; Ram & Arunachalam, 2024).

Agroforestry uses a variety of drone types, such as Fixed-Wing Drones, which are ideal for long-duration, high-area coverage but need open runways for takeoff and landing, Lighter-than-air (LTA) systems, which are less popular in agriculture but helpful for certain mapping purposes, and rotary-wing drones, which have excellent mobility and can hover, are perfect for small or inaccessible locations. Drones are equipped with a wide range of sensors, including RGB for visual mapping, multispectral sensors for vegetation health indices like NDVI, hyperspectral sensors for in-depth biochemical and stress analysis, LiDAR for mapping 3D structure and canopy height, thermal sensors for mapping water stress and microclimate, and Synthetic Aperture Radar (SAR) for biomass and structure even in cloud cover. (Devi et al., 2025; Maurya et al., 2022).

Flight planning, image acquisition, ortho-mosaic construction, feature extraction, and reporting are all common steps in a drone data workflow. A key component of using drones for agroforestry and agricultural monitoring effectively is flight planning, which maximises operational safety and efficiency while enabling the methodical collection of high-quality geospatial data. In order to obtain the required spatial coverage and resolution, a well-designed flight plan determines the best flight paths, altitudes, and image overlap while taking into account the survey objectives, field circumstances, sensor attributes, and regulatory constraints. This procedure is streamlined by contemporary flight planning technologies, which enable the automation of mission parameters, the setting of waypoints, and the management of contingencies for weather disruptions or battery constraints. Operators provide data consistency and repeatability through careful flight planning, which is essential for producing precise maps, keeping an eye on the health of the plants, and assisting with well-informed decision-making in agroforestry systems (Kudyba & Sun, 2025; Rejeb et al., 2022; Singh & Singh, 2025).

Applications in Agroforestry

Several studies (Chang et al., 2025; Devi et al., 2025; Ram & Arunachalam, 2024; Zhang et al., 2025) have demonstrated the effectiveness of combining drones, remote sensing, and GIS for agroforestry applications across different countries. For instance, in India, drone-based mapping improved tree survival monitoring accuracy by 35%. In Kenya, integration of UAV and Sentinel-2 satellite data enhanced yield prediction and informed policy-making. Meanwhile, in the United Kingdom, LiDAR technology facilitated precise assessments of canopy biomass and carbon stocks.

Key applications of these technologies in agroforestry include:

- Land Use Planning: Identify optimal sites for tree-crop integration using elevation, slope, and soil maps.
- Soil Mapping and Assessment: Use multispectral/hyperspectral imagery to monitor soil texture, moisture, and erosion risk.
- Vegetation and Health Monitoring: Generate spectral indices to assess canopy vigor and detect pest or nutrient stresses.
- Inventory and Stand Monitoring: Employ LiDAR/photogrammetry to estimate tree height, cover, and biomass for carbon accounting.
- Yield and Biomass Estimation: Calculate above-ground biomass and productivity for sustainable management.
- Biodiversity and Habitat Monitoring: Assess habitat connectivity, species diversity, and conservation progress.
- Post-Harvest and Disaster Assessment: Rapid damage quantification for insurance and recovery.

Case Studies

Elevation, slope, and soil maps were used in a geospatial land use planning study to determine the best locations for tree-crop integration in Ethiopia's Sile watershed. In a GIS environment, field-sampled soil properties were combined with digital elevation models and derived slope layers using weighted overlay analysis. Each criterion was standardised, weights were assigned using multi-criteria evaluation, and a composite suitability map was created as part of the technique. According to this analysis, about 51% of the watershed was highly suitable, 37% was moderately suitable, and the remaining portion was unsuitable because of steep slopes or poor soil for integrating crops like maize, banana, teff, and barley with trees. High field validation accuracy and practical agroforestry suggestions for each suitability class show that the results promote economic optimization, climatic resilience, and effective land use (Nuru et al., 2025).

Multispectral Sentinel-3 and hyperspectral near-infrared images were used in a soil mapping and assessment project in the European region to track soil texture, wetness, and erosion risk over large agricultural landscapes. In order to forecast soil properties, the methodology combined satellite spectral data with digital elevation model derivatives and then used machine learning techniques like Random Forest, Support Vector Machines, and artificial neural networks. Using spectral reflectance and texture features, this remote sensing analysis allowed for the quick classification of soil types, measurement of soil moisture, and identification of high erosion risk areas. Key findings showed that soil characteristics, including total nitrogen, sand, silt, clay content, and moisture, could be estimated with high accuracy, increasing prediction reliability by up to 19% when DEM derivatives were included. The method showed how multispectral and hyperspectral photography may produce reliable maps of soil properties and useful information for land management and precision farming (Jia et al., 2017).

In order to increase the accuracy of sustainable productivity evaluations, a study on yield and above-ground biomass estimation was carried out in maize fields utilising a mix of LiDAR point cloud data and UAV-based multispectral imaging. Using multispectral data sensitive to canopy features and LiDAR structural factors indicating vegetation height and structure, the methodology separated maize above-ground leaf biomass (AGLB) and stem biomass (AGSB). LiDAR-derived structural metrics and spectral vegetation indices were combined in multiple regression and partial least squares regression models to forecast total above-ground biomass (AGB). Plant density and height were among the field data gathered for the model's calibration. The PLSR model achieved an R2 of 0.86 and root mean square error (RMSE) of 72.28 g/m^2, indicating excellent correlations with biomass recorded in the field. Compared to utilizing either dataset alone, the accuracy of AGB estimation was increased by up to 19% when multispectral and LiDAR data were combined. For sustainable land management, this method facilitates accurate crop growth and productivity monitoring (Zhu et al., 2019).

Methodologies and Analytical Approaches

Land cover classification, biomass calculation, and species identification are all done using machine learning algorithms, particularly Random Forest (RF) and deep learning techniques (Chang et al., 2025; Dainelli et al., 2021). Statistical measures like R-squared, RMSE, and Kappa coefficient are frequently used to assess accuracy. Large datasets are managed, processed, and analysed using geo-relational databases and cloud platforms like Google Earth Engine (Devi et al., 2025).

Challenges and Limitations

There are a number of important obstacles to the use of UAVs (drones) in precision agriculture and agroforestry. Because UAV flights are subject to national and municipal aviation constraints, including airspace laws, registration procedures, and operational limitations like altitude, payload, and no-fly zones, which vary greatly by country and application, regulatory impediments sometimes present initial challenges. Operational efficiency is further limited by technical constraints. In addition to being vulnerable to un-favorable weather conditions including wind, rain, and extremely high temperatures, which can compromise mission success or sensor data quality, drones are usually limited by battery life, which reduces flight time and area coverage. Access to reliable cloud computing resources is frequently required for the effective management and analysis of large-volume geographical datasets due to the increased demands on data storage, processing capacity, and specialized software resulting from the integration of high-resolution sensors and large-scale data collecting. Additionally, the expensive initial cost of drone hardware, sensors, and related software infrastructure can be a barrier, particularly for smallholder farmers or institutions with low resources, even though operating costs often go down as the technology advances and grows. To fully realise the potential of UAV-driven agroforestry monitoring and management, these cumulative constraints must be solved by combining technical innovation, solid data management techniques, clear legal frameworks, and sustainable finance models (Dainelli et al., 2021; Maurya et al., 2022).

Future Prospects

The scope and impact of drones and remote sensing in agroforestry will be further expanded by integrating AI, real-time analytics, citizen research, and cloud-based processing. Precision management and scalability are made possible by these technologies, which also greatly advance sustainability and climate-smart agriculture objectives (Chang et al., 2025; Devi et al., 2025).

Conclusion

In agroforestry, drones and remote sensing have emerged as innovative tools that enable data-driven decision-making, dynamic monitoring, and efficient mapping. Despite challenges, further technological advancements will reinforce these technologies position in climate resilience and sustainable agroforestry initiatives/ management.

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Models for Economic Impact Assessment of Agroforestry Practices

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Introduction

Assessment of impact is essential for justifying research and technologies, as it provides critical evidence of their effectiveness and benefits. However, evaluating the impact of agroforestry systems presents several challenges, particularly due to their perennial nature. Unlike annual crops, agroforestry systems involve long-term growth and interactions among trees, crops, and livestock, making it difficult to measure immediate results. The benefits of such systems often develop over years, complicating short-term assessments and requiring methodologies that capture both immediate and long-term effects.

Additionally, the diversity of agroforestry systems adopted by farmers within a locality adds another layer of complexity. Farmers may implement varying combinations of tree species, crops, and management practices, which means that a one-size-fits-all assessment approach is inadequate. This variability complicates the process of selecting an appropriate sample of farmers for evaluation, as the impact can differ widely depending on the specific practices and contexts. Effective impact assessment must therefore be adaptable, incorporating diverse practices and long-term perspectives to accurately measure the multifaceted benefits of agroforestry systems and provide a robust justification for their adoption and continued support.
In this chapter, we focused on two crucial aspects: determining the appropriate sample size of farmers and selecting the methodologies for evaluating the impact of specific agroforestry systems.

Sample size

Selecting the right sample size is crucial because it must accurately represent the entire population. In agroforestry studies, this population refers not only to the people within a given area but also to all farmers practicing the same agroforestry method, like Anola-based or Ber-based systems. Ensuring the sample reflects this diversity is key to obtaining valid and generalizable results. Although both random and purposive sampling methods are viable for selecting samples, random sampling can be problematic since not all farmers may practice the specific agroforestry system in question. Consequently, we opted for purposive sampling in our study. Various methods are available for calculating sample size, but we propose using the Yamane formula for sampling agroforestry farmers (Yamane 1967). This formula is particularly effective for ensuring a statistically reliable and sufficient sample size, considering the specific variability and distribution within agroforestry practices.

$$\mathbf{n = \frac{N}{1+N(e\,)^2}}$$

where, n is the required sample size, N is the whole population (total agroforestry farmers) in the study region and e is the precision or sampling error which may varies between 5% to 10 %.

Conceptual framework for impact assessment methods:

Various impact assessment techniques are available in economic literature; each suited to different contexts depending on the nature of the intervention and the data at hand.

Matching methods like Propensity Score Matching (PSM) method are ideal for comparing treatment and control groups of agroforestry farmers with similar observed characteristics, especially when random assignment is not feasible. This approach helps control for confounding variables. **Inverse Probability Weighting with Regression Adjustment (IPWRA)** is advantageous for addressing complex treatment assignments and selection biases. It integrates weighting to adjust for treatment probabilities with regression adjustments for covariates, providing robust estimates in observational studies related to agroforestry practices. Both methods are applicable when analyzing annual field data at a specific point in time. **Difference-in-Differences (DID)** is most effective when assessing the impact of agroforestry intervention over time by comparing the pre- and post-treatment differences between a treated group and a control group of farmers at local as well as regional level. This method is particularly useful when randomization is not possible. **Economic Surplus Analysis** is suitable for evaluating the overall economic benefits of agroforestry systems, particularly in market contexts. It helps measure changes in consumer and producer surplus, providing a comprehensive view of economic impacts. Each method has strengths and is chosen based on the specific context and data availability.

The method of "Propensity Score Matching (PSM)"

Propensity Score Matching (PSM) method, a quasi-experimental technique which is widely used in impact assessment studies to deal with the problem of the missing counterfactual (Imbens and Wooldridge 2009). The first step in PSM is to estimate the predicted probability values of adoption (propensity scores) using the probit or logit model. We used the standard probit model (0=untreated and 1=treated) to obtain propensity score (Rosenbaum and Rubin 1983).

$$\mathbf{P\ (Xi\ ) = P\ (Z{=}1 \mid Xi\ )}$$

where, P(Xi) is the propensity score of the i^{th} household; P (Z=1|Xi) indicates the probability of treatment given the observable covariates (X) of i^{th} household.

To ensure that there is no systematic difference in the covariates of treated (farmers practicing agroforestry) and control (farmers do not practice agroforestry) groups in the matched sample, the balancing test was conducted. After that, three matching algorithms namely nearest neighbour matching (NNM), kernel based matching (KBM) with bandwidth 0.01 and radius matching (RM) with caliper 0.1 were employed. Though these matching procedures differ in creating the counterfactuals and assigning weights to the neighbours, and have their own limitations; using all the three methods provides robustness check of the results.
Finally, the impact of adoption of agroforestry practices on outcome variables (viz., farm income and system productivity) indicated by the average treatment effect on the treated (ATT) which is computed by restricting the matches to the households with propensity scores that fall in the area of common support (Caliendo and Kopeinig 2005):

$$\mathbf{ATT = E\{\ Y1_i - Y0_i\}}$$

where, E(Yi) denotes the expected value of the i^{th} outcome variable; 1 represents the treated, 0 otherwise.

Adoption of any farming practices is also governed by few unobserved confounders like risk attitude, neighbourhood adoption, slope of farm, perception of benefits (etc. If households in treated and control groups differ in these unobservables, the estimated ATT will be biased. Therefore, we conducted sensitivity analysis using bounding sensitivity method proposed by Rosenbaum (2002), for the ATT that are significantly different from zero to test whether inference regarding impact were sensitive to 'hidden bias' due to unobservables.

Matching quality and balancing test

Before discussing the impact, we underline here the quality of the matching through all three matching algorithm algorithms namely Nearest Neighbour Matching (NMM), Kernel (KBM) and Radius matching (RM), as the success of PSM lies in matching the observable covariates across treated and control groups (Becerril and Abdulai 2009). For example, in Table 1, Conforming to the requirement of balancing test, the Pseudo R^2 drops significantly to 0.7, 1.7 and 1.1 % for NNM, KBM and RM respectively, from around 22 % before matching.

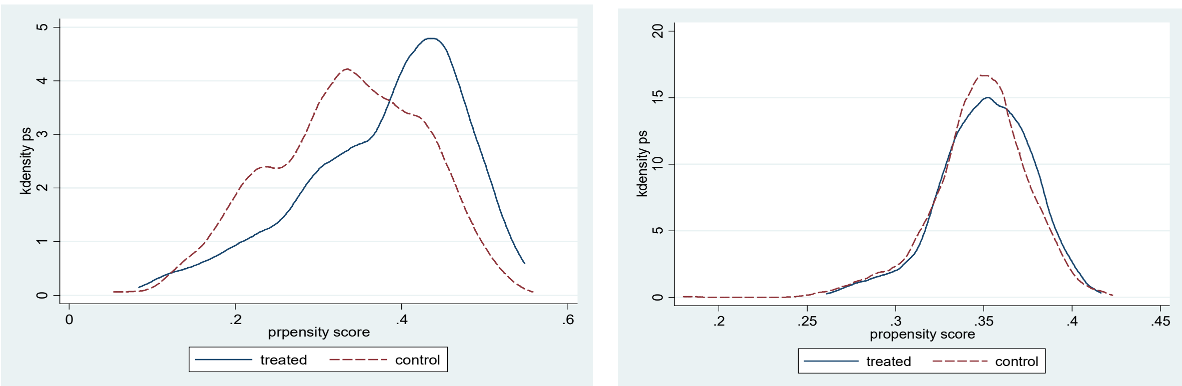
The higher and significant likelihood-ratio (LR) before matching signifies the presence of systematic differences between the treatment and comparison groups. The insignificant p-value for LR after matching indicates that these differences have been removed making the two groups comparable.

Further, the matching procedure led to substantial reduction in bias (69.78-77.17%) and as per the prerequisite criteria (Rosenbaum and Rubin 1983) the Mean Standardized Bias (MSB) is well below 20 % after matching. The low Pseudo R^2, insignificant p-values of the LR test, low MSB suggest that the specification of propensity is successful in terms of balancing the distribution of covariates between treated and control groups.

Table 1: Indicators of matching quality before and after matching

Test	Before matching	After matching		
		NNM	KBM	RM
Pseudo R^2	0.219	0.07	0.017	0.011
LR χ^2 (P-value)	47.43* (0.00)	6.21 (0.79)	8.74 (0.62)	7.24 (0.59)
Mean Standardized Bias	31.67	9.57	7.23	8.34
Total Bias reduction (%)		69.78	77.17	73.66

Source: Estimates based on survey data



(i) Unmatched sample (ii) Matched sample

Figure 2. Propensity scores distribution of treated and control farmers

Illustration in Fig. 2, depicts the propensity scores distribution for both treated and control group before and after matching suggests that control group are now more similar to treatment group as per the confounding factors. This observation suggests that the assumption of common support, a critical assumption for propensity score matching, is firmly upheld.

Visual observation of the Fig. 3 clearly indicates that the assumption of common support, a critical assumption for propensity score matching, is firmly upheld. Suitable matches of adopters (treated) and non-adopters (control) are shown as 'treated on support' while, adopters with bad matches from among the control are termed as 'treated off support.

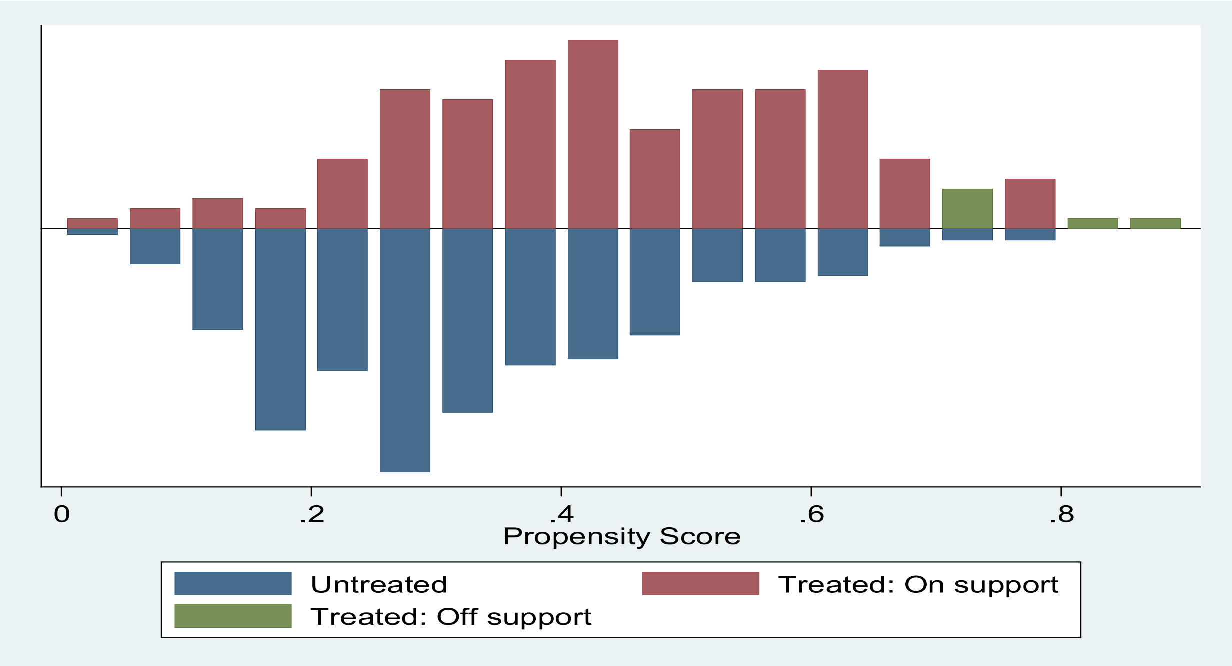


Figure 3. Propensity score distribution and common support

The method of "Difference-in-Difference"

The application of the Difference-in-Differences (DID) method in assessing the impact of agroforestry systems presents significant challenges, primarily due to the long-term nature of the benefits associated with tree species. This time lag makes it difficult to establish a clear pre-and post-intervention comparison, as the immediate effects may not fully capture the eventual benefits. Furthermore, DID relies on the assumption that trends in the treatment and control groups would have remained parallel in the absence of the intervention (Wooldridge 2010). However, in agroforestry, environmental and climatic factors can influence outcomes variables over time, complicating this assumption. As a result, distinguishing between the effects of agroforestry practices and external influences becomes challenging, potentially leading to biased estimates of impact. Additionally, the need for longitudinal data can impose practical constraints on research, such as resource availability and data collection efforts. Therefore, while DID can be a valuable tool in many contexts, its effectiveness in evaluating agroforestry systems is limited by the inherent time-dependent nature of the benefits involved.

The method of "Economic Surplus"

The economic surplus method is widely used and the most popular approach in assessing economic benefits from research as it requires the least data, and can be applied to the broadest range of situations. It works on the economic principles of consumer and producer surplus generated because of shift in supply function as a result of increase in production due to high yielding technologies. For understanding its application, let's consider a new tree variety (*ber tree with more fruit bearing*) has been developed.

The important steps in computing economic impact of the newly developed ber variety are discussed underneath:

Estimating production increases due to the research: the J parameter: The J parameter can be defined as the total increase in production that would be caused by adopting the new tree variety in the absence of any change in costs or price. It can readily be estimated as:

$$\boldsymbol{J} = \frac{(\Delta \mathbf{Y} \times \ \mathbf{t})}{\mathbf{Y}}$$

Where, ΔY represents yield gains (q/ha), Y is the average yield (i.e., total production divided by total acreage in hectares), and t is the adoption rate (i.e., the acreage under the new ber variety divided by the total acreage under the ber-based farming).

Estimating supply shifts: the K parameter: The K parameter may be defined as the net reduction in production costs induced by the new technology (new ber tree variety in the present case), combining the effects of increased productivity and adoption costs. It corresponds to a vertical shift in the supplycurve, given J and I, and could be computed using the elasticity of supply curve (es) asfollows

$$\mathbf{k} = \left[\frac{\boldsymbol{J}}{\mathbf{es}}\right] - \boldsymbol{c}$$

Estimating equilibrium quantity change (ΔQ): The change in quantity actually caused by research (ΔQ) depends on the shift in supply and the responsiveness of supply and demand. The ΔQ can be computed as:

$$\Delta Q = [Q \times e_S \times e_d \times k]/[e_S + e_d]$$

Where, ΔQ is total (aggregate) production of variety (kg) and e_d is elasticity of demand, drawn from economists' estimates.

Computing social gains and net gains: Economic benefits from the adoption of research is calculated as:

$$\textbf{Social gains}(\mathbf{SG}) = [\boldsymbol{k} \times \mathbf{P} \times \mathbf{Q}] \pm \frac{\mathbf{1}}{\mathbf{2}}[\boldsymbol{k} \times \mathbf{P} \times \Delta\mathbf{Q}]$$

In the above formula, we subtract the second term when data are observed after adoption (an ex-post study) and add it if adoption has not yet occurred (ex-ante). Net economic benefits is estimated after subtracting the costs of research (R) and extension (E) from the social gains as

$Netsurplus = SG - (R + E)$

Estimation of consumer and producer surplus:

Consumer surplus= (Z*Real price of the commodity* quantity of commodity produced (1+0.5*Z*price elasticity of demand))

Producer surplus= (real price*quantity of commodity produced*(K- Z)*(1+0.5*Z*price elasticity of demand)

Challenges in employing Economic surplus:

Assessing impacts using economic surplus methods involves several challenges. A primary issue is the lack of time series data on production, which hinders the analysis of long-term economic trends. Additionally, calculating the adoption rate of specific agroforestry practices, such as the ber-based system in this case, is complex due to the need for data on the total area under the system in the studied region. Selecting appropriate market prices for system outputs further complicates the assessment; even if yield advantages are estimated, determining which commodity's price to use is challenging. Moreover, the absence of specific elasticity parameters for agroforestry practices—such as supply and demand elasticities—limits the ability to model how changes in inputs or outputs affect economic surplus.

Despite these challenges, by making certain assumptions, it is possible to estimate the economic impact of agroforestry interventions using the economic surplus method, though results may need careful interpretation.

Conclusion

The challenges associated with the Difference-in-Differences (DID) method and the economic surplus approach—such as finding suitable counterfactuals and capturing dynamic market responses—suggest that econometric tools like matching techniques can serve as a strong alternative for evaluating the economic impact of agroforestry systems. By creating comparable groups based on observable characteristics, matching techniques help reduce selection bias and provide more reliable estimates of treatment effects. However, it's important to acknowledge that the choice of outcome parameters for measuring impact can be subjective and influenced by the researcher's viewpoint. For example, while some researchers may prioritize yield improvements or economic returns, others might focus on ecological benefits or social outcomes. This subjectivity can result in different interpretations of the effectiveness of agroforestry systems and affect policy recommendations. Consequently, while matching techniques offer valuable methodological rigor, the selection of outcome measures is crucial in shaping the conclusions about economic impact. Researchers should be transparent about their criteria and reasoning to enhance the validity and applicability of their findings in agroforestry impact assessments.

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Formulation of Carbon Credit Project in Agriculture, Forestry, and Other Land Use (AFOLU) Sector

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Grow Indigo, established in 2018 and incorporated on January 19, is driving a transformative revolution in regenerative agriculture across India. Leveraging the expertise of parent companies Mahyco and Indigo Ag, the company empowers smallholder farmers by enhancing profitability through innovative, sustainable practices that optimize yields, conserve resources, and promote environmental stewardship. Beyond providing solutions, Grow Indigo combines biological and digital tools to deliver timely insights, improve soil health, and foster resilient farming systems. Through initiatives in Biologicals, Carbon Farming, and Sustainable Produce, the company enables farmers to generate higher yields, access voluntary carbon markets, and help companies reduce scope 3 emissions, creating a sustainable and profitable future for all.

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Abstract

The Kyoto Protocol (1997) marked the first global commitment to reduce greenhouse gas (GHG) emissions through binding targets for industrialized nations and the introduction of carbon-market mechanisms such as International Emissions Trading, the Clean Development Mechanism, and Joint Implementation. Structural limitations, including the Annex I versus non-Annex I divide and uneven participation, weakened its long-term effectiveness, paving the way for the Paris Agreement (2015). Paris established a universal climate framework with Nationally Determined Contributions (NDCs) and Article 6 mechanisms, enabling international carbon trading (Article 6.2 and 6.4) and non-market cooperation (Article 6.8). Within this framework, the Agriculture, Forestry, and Other Land Use (AFOLU) sector responsible for nearly a quarter of global GHG emissions plays a critical role due to its diffuse, community-linked emission sources. AFOLU carbon projects span REDD+, Afforestation/Reforestation, Improved Forest Management, Agricultural Land Management, Wetland Restoration, and Avoided Conversion of Grasslands.

Project development involves feasibility assessments, baseline establishment, demonstration of additionality, and detailed planning of field interventions. Robust carbon accounting relies on approved methodologies to quantify emissions, address leakage, and manage non-permanence risks through buffer contributions. Monitoring, Reporting, and Verification (MRV) systems, followed by independent validation and verification, ensure environmental integrity, leading to credit issuance through Project Review and Response (PRR) cycles. Effective financial structuring, governance frameworks, safeguards, and equitable benefit-sharing underpin long-term sustainability. Finally, credit commercialization through exchanges, brokers, or direct corporate offtake transforms verified AFOLU climate benefits into economic returns, reinforcing global mitigation efforts.

Key word: AFOLU, Article 6, REDD+, ARR, MRV, Leakage, non-permanence risk & Carbon credit

Introduction

The Kyoto Protocol, adopted in 1997 and in force since 2005, was the first major global treaty to reduce greenhouse gas (GHG) emissions. It required 41 industrialized countries and the EU to cut six key GHGs CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 by 5.2% below 1990 levels during the 2008–2012 commitment period. Kyoto introduced the UN's first carbon market mechanisms: International Emissions Trading (IET), Clean Development Mechanism (CDM), and Joint Implementation (JI). These allowed countries to trade Assigned Amount Units, generate Certified Emission Reductions via projects in developing countries, and conduct bilateral reduction projects, laying the basis for global carbon trading. However, structural tensions emerged from Kyoto's binary classification of Annex I (industrialized) and non-Annex I (developing) countries, which imposed binding targets only on the former. As emerging economies like China and India had no reduction obligations, industrialized nations viewed the system as uneven. The U.S. never ratified the Protocol, and countries such as Canada, Japan, and Russia later withdrew. Falling demand and oversupply of credits weakened Kyoto, leading to the Paris Agreement (2015). Paris required all countries to submit Nationally Determined Contributions (NDCs) and created Article 6, enabling voluntary international carbon-market cooperation. Rules finalized at COP26 (2021) now guide Article 6 markets, which operate alongside the expanding voluntary carbon market (VCM).

Article 6 of the Paris Agreement allows countries to voluntarily cooperate in meeting their NDCs by transferring carbon credits from verified emission reductions. Article

6.2 enables trading of internationally transferred mitigation outcomes (ITMOs) with rules to ensure transparency and avoid double counting. Article 6.4 creates a UN-supervised mechanism, like the Kyoto Protocol's CDM, for producing and trading high-quality emission reductions between countries. Article 6.8 supports non-market approaches, promoting cooperation through climate finance, technology transfer, and capacity building without involving carbon trading. There are various sectoral scopes under Article 6 of the Paris Agreement, within which projects, activities, and methodologies can be developed for creating verified carbon units (VCUs). These include: 1. Energy (renewable and non-renewable), 2. Energy distribution, 3. Energy demand, 4. Manufacturing industries, 5. Chemical industry, 6. Construction, 7. Transport, 8. Mining and mineral production, 9. Metal production, 10. Fugitive emissions from fuels (solid, oil, and gas), 11. Fugitive emissions from industrial gases (halocarbons and sulphur hexafluoride), 12. Solvent use, 13. Waste handling and disposal, 14. Agriculture, forestry, and other land use (AFOLU), 15. Livestock and manure management, and 16. Carbon capture and storage.

The Agriculture, Forestry, and Other Land Use (AFOLU) sector occupies a critical role in the global climate system, contributing approximately 23 to 24 percent of total anthropogenic greenhouse gas (GHG) emissions **(IPCC, 2014**). These emissions arise primarily from deforestation, biomass burning, soil degradation, methane generation from livestock and rice cultivation, and nitrous oxide emissions from nitrogen fertilizers. In contrast to industrial sectors, where emissions are concentrated at point sources and mitigated through technology upgrades, AFOLU emissions are inherently diffuse and closely tied to community-managed landscapes. Effective mitigation within this sector therefore demands an integrated approach that combines scientific rigor with participatory land management, institutional coordination, and continuous monitoring.

Classification of AFOLU Carbon Projects

AFOLU carbon projects are broadly categorized under established global standards such as Verra's Verified Carbon Standard (VCS), Gold Standard, ART TREES, Plan Vivo Standard (PVS) and the American Carbon Registry (ACR) etc. Among the most widely deployed categories is REDD+ (Reduced Emissions from Deforestation and Forest Degradation), which aims to prevent forest carbon losses driven by illegal logging, agricultural expansion, slash-and-burn practices, grazing pressures, and infrastructure development. Another major category is Afforestation, Reforestation, and Revegetation (ARR), which enhances carbon stocks through the establishment of tree cover using plantation activities, assisted natural regeneration, agroforestry systems, and large-scale restoration of degraded areas. Improved Forest Management (IFM) initiatives strengthen carbon retention in existing forests by incorporating reduced-impact logging, extended harvest cycles, fire prevention mechanisms, and conservation-based management. Agricultural Land Management (ALM) focus on reducing GHG emissions and enhancing soil carbon through improved nitrogen management, rice methane reduction techniques, conservation tillage, cover cropping, and regenerative agriculture. Wetlands Restoration and Conservation (WRC) projects address significant mitigation potential through peatland rewetting, hydrological restoration, mangrove rehabilitation, and estuarine conservation. Additionally, Avoided Conversion of Grasslands and Shrublands (ACoGS) projects prevent the transformation of native grasslands and shrublands into croplands, infrastructure, or other land uses, thereby preserving soil carbon and biodiversity. These projects maintain ecosystem services, support sustainable grazing, and reduce long-term carbon emissions from soil disturbance and vegetation loss. Community involvement and sustainable land management practices are key to their success.

Feasibility assessment

Project formulation begins with a systematic feasibility assessment designed to determine whether the proposed area or farming system is eligible and viable for carbon project development. A project developer evaluates legal eligibility, carbon sequestration potential, community willingness to participate, financial justification, scalability of proposed interventions, and the ability to monitor the project over a long-term crediting period. Biophysical feasibility assessments examine site-specific climate, soil characteristics, hydrological conditions, vegetation cover, fire history, and land-cover trends, often with the support of remote sensing tools such as Sentinel-2 NDVI and NDMI indices, Landsat-based deforestation datasets, SRTM elevation data, and global soil databases like Soil Grids. Social feasibility assessments focus on understanding community land-use patterns, stakeholder interests, institutional structures, and the clarity of land tenure and user rights.

Establishing the Reference/Baseline Scenario

Baseline development is a core technical element of AFOLU project design, serving as the "business-as-usual" scenario against which emission reductions or removals are measured. Establishing the baseline requires a detailed understanding of historical land use over a period of 10 years, analysis of deforestation drivers or agricultural trends, assessment of socio-economic influences, evaluation of policy frameworks, and collection of biophysical field data. Depending on the project type and methodology requirements, developers may employ historical average trends, dynamic baselines, land-use change modelling, stratified sampling, or combined field inventory and remote sensing approaches.

Demonstrating Project Additionality

Additionality is a critical criterion ensuring that project mitigation outcomes would not have occurred without carbon finance. Project developers must demonstrate that the activities are not legally mandated, are not common practice in the region, and require carbon revenue to be financially viable. This justification is supported by financial analyses, regulatory assessments, surveys on current land management practices, and investment gap evaluations.

Once eligibility and additionality are established, the project’s field activities are designed.

Planning Project Activities

Forestry projects typically involve tree planting, species selection, nursery establishment, site preparation, and long-term maintenance, along with protection measures such as fencing and fire control. Assisted natural regeneration strategies focus on removing stressors to natural forest growth, such as grazing and invasive species, and may include selective enrichment planting. Improved forest management introduces controlled harvesting techniques, fire management strategies, and conservation zoning. Agricultural interventions vary by crop system; rice methane reduction projects rely on techniques such as alternate wetting and drying, direct seeding, mid-season drainage, and improved fertilizer management. Soil carbon enhancement projects emphasize regenerative practices including minimal tillage, cover cropping, compost application, organic residue incorporation, and rotational grazing. Community livelihood components are often integrated into AFOLU carbon project design to create sustainable, low-emission income opportunities, provide training, and share carbon revenue. These interventions reduce reliance on emission-intensive practices, enhance community well-being, and simultaneously contribute to multiple Sustainable Development Goals (SDGs), including climate action and biodiversity conservation.

Carbon Accounting

Carbon accounting follows standards-based methodologies to ensure accurate, transparent, and verifiable estimation of greenhouse gas (GHG) reductions. These methodologies, available under recognized frameworks such as Verra’s VCS, Gold Standard, ART TREES, Plant Vivo etc. provides detailed procedures for determining baseline emissions, quantifying project-induced reductions, and accounting for leakage and non-permanence risks. They specify which carbon pools and GHG sources to include (aboveground and belowground biomass, deadwood, litter, and soil organic carbon, while emissions may include CO_2 from biomass loss, CH_4 from rice paddies, N_2O from fertilizer application, and CO_2 from fossil fuel use), sampling protocols for biomass and soil carbon, emission factors, and monitoring frequency. These data are analysed using allometric equations, statistical modelling tools, GIS-based carbon mapping, and remote sensing biomass estimation techniques. By adhering to these approved methodologies, project developers can produce credible carbon credits, facilitate third-party verification, and maintain consistency in reporting while aligning with global climate mitigation standards.

Leakage management

Leakage management is essential to ensure that emission reductions are not undermined by unintended effects beyond the project boundary. Activity-shifting leakage may occur when communities relocate deforestation or land conversion activities outside the project area, while market leakage may arise when reduced production within the project area leads to increased extraction elsewhere. Developers mitigate leakage through livelihood diversification, improved household energy efficiency, alternative grazing systems, and formalized community agreements. Quantified leakage is deducted from the total carbon credit volume.

Non-permanence risk assessments

Non-permanence risk assessments is a core requirement in AFOLU carbon projects because carbon stored in forests, soils, and land-use systems can be reversed due to natural disturbances or human activities. Unlike engineered or industrial carbon projects, land-based carbon benefits are vulnerable to risks such as fires, pests, storms, illegal logging, grazing pressure, and land-use conflicts. Therefore, all major carbon standards require project developers to conduct systematic non-permanence risk assessments and apply mitigation measures to ensure long-term carbon stability. Standards require a structured risk assessment, and a portion of issued credits typically between 10 and 20 percent is contributed to a shared buffer pool to insure against potential reversals. Under VCS, non-permanence risks are evaluated using the AFOLU Non-Permanence Risk Tool, which requires scoring a wide range of factors including project management quality, financial viability, land tenure security, natural disturbance history, and community engagement. Based on the calculated risk score, a mandatory percentage of carbon credits is deposited into a non-tradable buffer pool to insure against potential carbon reversals. The buffer contribution may be reduced if the project demonstrates strong safeguards, diversified livelihoods, or effective fire and pest management. Whereas under the Gold Standard, the required buffer for non-permanence risk is 20% of issued CO_2 certificates, which must be contributed to the "Gold Standard Compliance Buffer" to insulate against potential reversals.

Monitoring, Reporting, and Verification (MRV)
Monitoring, Reporting, and Verification systems ensure transparency and integrity throughout the crediting period. Monitoring plans specify timelines for biomass measurement, satellite monitoring, soil resampling, farmer practice verification, and hydrological assessments. Reports compiled for verification include monitoring data, inventory results, GIS shapefiles, community engagement documentation, and detailed activity evidence.

Independent third-party assessments
Independent third-party or Validation and Verification Bodies (VVBs), assessments are conducted by accredited, impartial organizations or auditors to ensure compliance with internationally recognized carbon standards such as VCS, Gold Standard, or Plan Vivo. These assessments are fundamental to establishing the credibility, transparency, and integrity of the resulting carbon credits. The assessments comprise two critical stages: validation and verification. During the validation phase, the third party rigorously reviews the project design, baseline scenarios, additionality demonstration, and methodological framework to confirm that the project is capable of delivering real, measurable, and additional emission reductions or removals. During verification, the auditors evaluate project implementation, field-level measurements, monitoring data, and adherence to the approved methodology, ensuring that reported emission reductions are accurate, consistent, and verifiable. Additionally, they assess the application of safeguards, leakage management strategies, and non-permanence risk mitigation measures, ensuring environmental and social integrity. Upon successful assessment, auditors provide formal assurance that the project's carbon credits represent genuine, permanent, and high-quality climate benefits, and recommend the issuance of VCUs. Such independent evaluations are essential to maintain stakeholder confidence and uphold market integrity in the global carbon trading ecosystem.

Post-Verification Process and PRR Review Rounds Leading to Issuance
Once the monitoring period ends, the VVB conducts the required assessments, beginning with validation to confirm the project's design, baseline, methodology, and eligibility, followed by joint validation–verification or full verification, where the VVB audits field data, monitoring results, safeguards, and carbon calculations in a

combined or sequential review. After completing these assessments, the VVB prepares and signs the consolidated Validation and Verification Report (DVR), which, together with the Monitoring Report and supporting evidence, is submitted to the registry. The registry then initiates the Project Review and Response (PRR) process, where technical reviewers evaluate all documentation and may raise queries through one or more review rounds until all issues are resolved. Once the PRR is finalized and approved, the registry confirms the verified emission reductions or removals and issues the corresponding carbon credits, assigning unique serial numbers and generating the official Carbon Credit Issuance Certificate. These certified credits can then be traded, transferred, or retired, completing the full validation, joint validation–verification, and issuance cycle.

Financial Structuring & Economic Modelling

Financial structuring is a fundamental element of project success. Costs include baseline studies, field operations, nursery development, monitoring equipment, verification fees, community benefit-sharing commitments, and administrative overhead. Revenue projections depend on estimated credit volumes, carbon market prices, and premiums associated with biodiversity or social co-benefits. Transparent benefit-sharing mechanisms ensure that communities receive equitable compensation through fixed allocations, performance-based payments, or reinvestment in local infrastructure and development.

Governance, Safeguards, and Long-Term Sustainability

Governance frameworks and safeguard mechanisms ensure long-term project sustainability. Standards require adherence to social and environmental safeguards, including protection of indigenous rights, biodiversity conservation, and the establishment of grievance redress systems. Projects must establish governance structures such as Project Management Units (PMUs), community-level committees, monitoring teams, financial administration cells, and grievance committees. Capacity-building initiatives equip communities and field teams with knowledge on silviculture, soil management, monitoring technologies, and financial literacy.

Selling of Carbon Credits

After the carbon credits are officially issued into the project registry, next step focuses on their commercialization, beginning with the selection of the most appropriate selling strategy. Project owners may choose to list credits on carbon exchanges for transparent pricing and fast transactions, work with brokers who can secure customized deals and access established buyer networks or pursue direct corporate sales that often deliver premium pricing and long-term offtake agreements. Once the preferred channel is selected, the next step is to establish an appropriate pricing structure, considering factors such as project type, co-benefits, market demand, and buyer requirements. With pricing in place, the project developer enters the contracting phase, where the volume of credits, vintage year, delivery terms, and payment conditions are formalized through sales agreements, whether spot sales, forward contracts, or multi-year commitments. Following contract execution, the credits are transferred to the buyer's registry account or retired on their behalf, depending on whether they intend to trade them further or claim emissions reductions. The process concludes with payment settlement according to the agreed terms, ensuring that revenue flows back to the project and its stakeholders. Together, these steps complete the full commercialization cycle, transforming verified AFOLU carbon credits into tangible financial returns.

Conclusion

The development of AFOLU carbon projects represents a highly multidisciplinary endeavour that seamlessly integrates environmental science, land and forest management, socio-economic planning, financial structuring, and regulatory compliance. These projects go beyond simple carbon sequestration; they require a holistic understanding of ecosystem dynamics, soil health, biodiversity conservation, and climate mitigation potential, alongside strong engagement with local communities and stakeholders. Successful AFOLU projects rely on scientific rigor to accurately model baselines, quantify greenhouse gas reductions, and ensure long-term carbon permanence. At the same time, active community collaboration is crucial to implement sustainable land-use practices, enhance livelihoods, and foster ownership of project outcomes. Transparent governance, robust monitoring systems, and adherence to international standards safeguard the credibility and integrity of generated carbon credits. By harmonizing ecological stewardship with socio-economic benefits, AFOLU projects not only contribute to climate change mitigation but also promote resilient landscapes, improved agricultural productivity, and enhanced community well-being. When designed and executed effectively, these projects become a powerful mechanism for achieving sustainable development goals, delivering measurable climate impact while empowering communities and preserving vital ecosystems for future generations.

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NTFP-based agroforestry systems for livelihood security in the semi-arid tract of India

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Introduction

The term "semi-arid tract" generally refers to any region with a semi-arid climate (low, erratic rainfall of 250-600 mm/year), while "semi-arid tropics (SAT)" specifically denotes a hot semi-arid region that lies within the tropical zone. The key distinction is the geographic location and specific temperature range. Semi arid tract can be in tropical, subtropical, or temperate zones (e.g., cold semi-arid steppes, Cold deserts) while SAT is limited strictly within the tropical and subtropical latitudes. We can say semi-arid tropics (SAT) are a subset of the broader "semi-arid tract" defined by their consistent, high-temperature tropical location and specific monsoon-influenced rainfall patterns. Organizations like the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) focus specifically on the unique agricultural challenges of the SAT regions worldwide. The semi-arid tropics (SAT) in world cover an area of about 20 million km². Kampen and Burford (1980) estimated that 700 million people live in this zone, nearly half of them in India. This population has increased over two billion people currently live in global drylands (hyper-arid, arid, semi-arid, and dry sub-humid areas), which cover about 41% of the Earth's terrestrial surface. The Indian arid zone is one of the most densely populated arid zones in the world. The SAT cover most of West, East and the southern part of central Africa; most of India, northeastern Myanmar, northeastern Thailand and northern Australia; most of Mexico; and large parts of eastern and central South America. The SAT environment is characterized by high atmospheric water demand; a high mean annual temperature (>18°C); and a low, variable annual rainfall (400 to 1900 mm) (Swindale, 1982). The climate of most of the SAT is monsoonal, with over 90 percent of the rainfall occurring in the period of April-October in the Northern Hemisphere and October-April in the Southern Hemisphere.

Semi-arid tracts of India—covering regions of Rajasthan, Gujarat, Maharashtra, Telangana, Karnataka, and Andhra Pradesh which are characterized by low, irregular rainfall, degraded soils, and high climatic risk. Low to medium rainfall (below 700 mm on average), unpredictable and often insufficient for crops, with long dry seasons. High temperatures and solar radiation are also common. These are a large agro-ecological zone characterized by low, erratic rainfall, high temperatures, and poor soils, encompassing over one third of the country's area. This zone is crucial for agriculture, supporting nearly half of the nation's food grain production and two-thirds of its oilseed output, despite facing constraints like drought, soil erosion, and water logging. Soils are often poor in nutrients, and the region is prone to degradation, including salinity and erosion. The region is heavily reliant on rainfed farming, and is a significant producer of food grains and oilseeds. Major crops include Sorghum, millet, pigeon pea, chickpea, groundnut, and cowpea is vital for food and oil. The region is highly vulnerable to drought, which can impact the livelihoods of millions. There are large gaps between current and achievable crop yields, often due to water shortages and soil degradation.

Agroforestry is a major feature of world agriculture and as per FAO estimates agroforestry occurs on >43% of agricultural land globally and that 78% of agroforestry area is in the tropics. Estimated 3.5–5.8 billion people use NTFPs in some form (median estimates ~5.7 billion), with ~2.7–2.8 billion rural users in the Global South showing extremely broad reliance on NTFPs for food, medicine and income. Global area estimates for agroforestry varies by methodology and classifications from ~307–823 Mha for different classifications or up to higher ~1,023 Mha because definitions differ (trees on farms, silvopasture, hedgerows, etc.). Recent national estimates place India's agroforestry area in the ~25–28 million hectares which is ~8–8.6% of total geographical area. An IGNFA, Dehraun summary estimated an all-India average value of ~₹1,671/ha and a gross value estimate of ~₹41.89 billion. India has a formal National Agroforestry Policy (2014), various state schemes, watershed and wasteland programmes that support tree planting on farms, and the Forest Rights Act (2006) which influences community access to NTFPs and these provide the enabling institutional framework for scaling NTFP agroforestry.

Non-Timber Forest Products (NTFP) or Non-Wood Forest Products (NWFP)

Any forest-derived products that are not timber or wood, such as fruits, nuts, mushrooms, medicinal plants, resins, and fibers. These products are still harvested from natural forests and they play a vital role in the economy and livelihoods of local and indigenous communities / tribals by providing income and food security. Examples -Food and beverage: Fruits, nuts, berries, seeds, mushrooms, and honey. Medicinal and aromatic: Medicinal plants, herbs, and essential oils. Fibers and materials: Bamboo, rattan, and other fibers used for construction, weaving, and crafts. Resins and gums: Products like gum arabic, resins, and oils derived from trees. Animal products: Products such as game animals, fur-bearers, insects, lac, and silk. Other: Foliage, peat, and fuelwood. Important NWFP yielding plants which are /can be used in agroforestry sytems for adoption in different ecologies of India are presented below.

Flavours and Fragrances (Essential oils)

Grass Oils: Lemon grass oil (*Cymbopogon flexuosus*), West Indian lemon grass oil (*Cymbopogon citratus*), Palmarosa oil (C*ymbopogon martinii* var. *motia*), Ginger grass oil (C*ymbopogon martinii* var. *sofia*), Citronella oil (*Cymbopogon nardus* var. *winterianus*), Vetiver oil (*Vetiveria zizanioides*)

Wood Oils: Sandalwood oil (*Santalum album*), Agar oil (*Aquillaria agalocha*), Deodar oil (*Cedrus deodara*), Pine oil/ Turpentine oil (*Pinus roxburghii*), Linaloe oil (*Bursera delpechiana*), Cedar oil (*Juniperus macropoda*)

Leaf Oils: Eucalyptus oil (*Eucalyptus globulus*), Lemon scented gum oil (*Eucaylyptus citriodora)*, Camphor oil (*Cinnamomum camphora*), Pine needle oil (*Pinus roxburghii*), Mint oil (*Mentha* spp.), Patchouli oil (*Pogostemon patchouli*), Geranium oil (*Pelargonium graveolens*), Wintergreen oil (*Gualtheria fragrantissima*)

Root/Rhizome Oils: Costus oil (*Saussurea lappa*), Indian valerian oil (*Valeriana wallichii*), Curcuma oil (*Curcuma aromatica*), Cyperus oil (*Cyperus scariosus*), Sweet flag oil (*Acorus calamus*)

Flower Oils: Jasmine oil (*Jasminum officinale*), Rose oil (*Rosa damascena*), Keora oil (*Pandanus odoratissimus*), Tagtes oil (*Tagetes indica*), Champa oil (*Michelia champaca*), Lavander oil (*Lavandula officinalis*), Cassie perfume (*Acacia fernesiana*), Clove oil (*Syzygium aromaticum*),

Other Essential Oils: Citrus oil/Lime oil (*Citrus aurantifolia*), Petgrain oil (*Citrus aurantium* and *Citrus limettioides*), Orange oil (*Citrus sinensis*), Mandarin oil (*Citrus reticulata*), Cinnamoum oil (*Cinnamomum zeylanicum*), Nutmeg oil (*Myristica fragrans*), Salai gum oil (*Boswellia serrata*)

Gums, Resins and Latex

Acacia Gums: Babul (*Acacia nilotica*), True gum arabic (*A. senegal*), Khair (*A. catechu*), *A. modesta*, *A. fernesiana*, *A. leucophloea*

Other Gums: Karaya gum (*Sterculia urens*), *Cochlospermum religiosum*, Semal (*Bombax ceiba*), *Astragalus heratensis,* Kapok (*Ceiba pentandra*), Hog tragacanth (*Prunus amygdalus*), Cherry gum (*Prunus armeniaca*), Bengal kino (*Butea monosperma*), Gum kino (*Pterocarpus marsupium*), Jhingan gum (*Lannea coromandelica*), Salai gum (*Boswellia serrata*), Moringa gum (*Moringa pterygosperma*), Dhaura/ Ghatti gum (*Anogeissus latifolia*), Semla gum (*Bauhinia retusa*), Madiata gum (*Adenanthera pavonina*), Gutta percha gum (*Dichopsis polyantha*), Eucalyptus kino (*Eucalyptus globulus*), Lemon scented gum (*Eucalyptus citriodora*)

Minor Gums: *Albizia chinensis, A. odoratissima, A. procera, Anacardium occidentale, Azadirachta indica, Bauhinia purpurea, B. racemosa, B. variegata, Chloroxylon swietenia, Feronia limonia, Mangifera indica, Terminalia alata, T. bellerica, Agele marmelos, Ailanthus excelsa, Pithecellobium dulce, Spondias pinnata, Borassus flabellifer, Buchanania latifolia, Calophyllum apetalum, C. elatum, C. inophyllum, Chukrasia tabularis, Delonix regia, Elaeodendron glaucum, Gardenia turgida, Gaurga pinnata, Macaranga peltata, Prosopis juliflora, P. cineraria, Zizyphus sativa*

True Resins: Balck dammar (*Canarium strictum*), Rock dammer (*Hopea odorata*), Green dammar (*Shorea tumbuggaia*), White dammar (*Vateria indica*), Amber (*Pinus succinfera*), Lacquer (*Rhus vernicifera*), Shell lac (*Laccifer lacca*), Mastic (*Pistacia lentiscus*), Sand arac (*Callitris quadrivalvis*), Storax (*Atingia excelsa*)

Other True Resins: *Abies excela, A. webbiana, Ailanthus malabarica, Cannabis sativa, Carica papaya, Daemonorops kurzianus, Juniperus communis, Liquidambar orientalis, Styrax benzoin*

Oleo Resins: Salai gum (*Boswellia serrata*), Gurjan oil (*Dipterocarpus turbinatus*), *Kingiodendron pinnatum, Cedrus deodara, Erythroxylon monogynum, Melanorrhoea usitata, Pinus insularis, Pinus roxburghii, Pinus wallichiana, Shorea robusta*

Gum Resins: Gamboge (*Garcinia morella*), Myrrah/Gugal (*Commiphora mukul*), Galbanum (*Ferula galbaniflua*), Asafoetida (*Ferula asafoetida*), *Diospyros peregrina*, Dikamali/ Cumbi gum (*Gardenia gummifera*)

Latex: Chilte (*Cnidoscolus* spp.), Chicle (Manilkara zapota), Rubber latex (*Hevea brasiliensis*)

Tree Born Oilseeds (TBOs)

Jatropha curcas, Pongamia pinnata, Madhuca indica, Simmondsia chinensis, Azadirachta indica, Simarouba glauca, Shorea robusta, Mangifera indica, Garcinia indica, Salvadora oleoides, S. persica, Ziziphus mauritiana, Prunus armeniaca, Aleurites Montana, Aleurites fordii, Thespesia populnea, Moringa oleifera, Calophyllum inophyllum, Schleichera oleosa, S. trijuga and *Actinidaphne hookeri*

Fibres and Flosses

Fibres: *Agave sisalana*, *Streculia villosa*, *Abroma augusta*, *Abutilon* spp., *Ananas cosmosus*, *Antiaris toxicaria*, *Boehmeria nivea*, *Borassus flabellifer*, *Cannabis sativa*, *Cordia dichotoma*, *C. rothii*, *Giradinia heterophylla*, *Grewia glabra*, *G. elastica*, *G. optiva*, *Hibiscus* spp., *Malachra capitata*, *Marsdenia tenacissima*, *M. volubilis*, *Phormium tenax*, *Sansevieria roxburghiana*, *Sesbania bispinosa*, *Sida rhombifolia*, *Sterculia foetida*, *S. urens*, *Themeda arundinacea*, *Trema orientalis*, *Typha elephantina*, *Urena lobata*, *Oreocnide integrifolia*
Flosses: Indian Kapok (*Bombax ceiba*), Kapok or Silkcotton (*Ceiba pentandra*), *Cochlospermum religiosum* (Silk cotton tree), *Calotropis gigantea* (Aak, Akund floss)

Dyes/ Colourants

Wood Dyes: Kutch dye (*Acacia catechu*) and other dyes from *Artocarpus heterophyllus*, *A. lakoocha*, *Pterocarpus santalinus*, *Caesalpinia sappan*

Bark Dyes: *Terminalia tomentosa*, *Acacia concinna*, *A. farnesiana*, *A. leucophloea*, *Alnus* spp., *Casuarina equisetifolia*, *Manilkara littoralis*, *Myrica esculenta*, *Ventilago madraspatana*

Flower and Fruit Dyes: *Mallotus philippensis*, *Woodfordia floribunda*, *Bixa orellana*, *Butea monosperma*, *Toona ciliata*, *Nyctanthes arbortristis*, *Mammea longifolia*, *Wrightia tinctoria*, *Crocus sativus*

Root Dyes: *Berberis aristata*, *Datisca cannabina*, *Morinda tinctoria*, *Punica granatum*, *Rubia cordifolia*

Leaf Dyes: *Indigofera tinctoria*, *Lawsonia inermis*

Tannins:

Bark Tans: *Acacia mearnsii*, *A. dealbata*, *A. nilotica*, *A. auriculiformis*, *Cassia fistula*, *Cassia auriculata*, *Rhizophora mucronata*, *Ceriops roxburghiana*, *Terminalia arjuna*, *Shorea robusta*

Fruit Tans: *Terminalia chebula*, *T. bellerica*, *Acacia nilotica*, *Emblica officinalis*, *Zizyphus xylocarpa*, *Caesalpinia coriaria*

Leaf Tans: *Anogeissus latifolia*, *Emblica officinalis*, *Carissa spinarum*

Gall Tans: *Tamarix* spp.

Medicinal Plants

Root Drugs: *Podophyllum hexandrum* (Bankakru), *Saussuria lappa* (Kuth), *Aconitum heterophyllum* (Atis), *Acorus calamus* (Bach), *Rheum emodi* (Rubabrb), *Picrorhiza kurrooa* (kuru), *Vallerina wallichii* (Banahfsa), *Asparagus ascendans* (Satavar), *Glycyrrhiza glabara* (Mulathi), *Berberis* spp., *Discorea deltoides* (Medicinal yam), *Rauvolfia serpentina* (Sarpgandha), *Nardostychus jatamansi*, *Colchicum leuteum*, *Abroma angusta*, *Hemidesmus indicus*, *Sarsaparilla* spp., *Urgenia indica*

Bark Drugs: *Chichona* spp., *Holarrhina antidysentrica*, *Soymida febrifuga*, *Alistonia scholaris*, *T. arjuna*

Flower, Fruit and Seed Drugs: *Artmissia* spp., *Strychnos nux vomica*, *Agel marmelos*, *Ricinus communis*, *Cassia fistula*, *Chenopodium ambrosoides*, *Pyrethrum* spp., *Casealpinia crista*, *Tamaridus indica*, *Terminalia bellerica*, *T. chebula*, *Embelica officinalis*, *Plantago ovata*

Leaf Drugs: *Ephedra gerardiana*, *Vitex nugendo*, *Gultheria fragrantissima*, *Mentha arvensis*, *Hyoscymus niger*, *Ocimum kilimandscharium*, *Azadirachta indica*, *Cannabis sativa*, *Atropa acuminata*, *Datura* spp., *Swertia chirata*

Edible Plant Products

Edible Fruits: Chironji (*Buchanania lanzan*), Aonla (*Emblica officinalis*), Tamarind (*Tamarindus indica*), Bael (*Aegle marmelos*), Wood apple (*Feronia elephantum*), Jackfruit/Kathal (*Artocarpus heterophyllus*), Barhal (*Artocarpus lakoocha*), Kala lakuch (*Artocarpus gomezianus*), Jamun (*Syzygium cuminii*), Custard apple/Sarifa (*Annona squamosa*), Ramphal (*Annona reticulata*), *Carissa opaca*, Karaunda (*Carisa carandas*), Timla (*Ficus auriculata*), Pakar (*Ficus infectoria*), Parphuta (*Ficus nerifolia*), Bedu (*Ficus palmata*), Gular (*F. glomerata*), Ber (*Zizyphus jujuba*), Jangali jalabi/ Madras thorn/ Manila tamrind (*Pithecellobium dulce*)

Edible Nuts: Cashew nut (*Anacardium occidentale*), Chilgoza (*Pinus gerardiana*), Walnut (*Juglans regia*), Almond (*Prunus dulcis*)

Edible Flowers: Mahua (*Madhuca indica*), *M. longifolia*, *Musa* spp, *Bombax ceiba*, *Bauhinia purpurea*, *Alangium salvifolium*, *Ficus glomerata*, *Sesbania grandiflora*, *Rhododenron arboreum*

Roots and Tubers: *Amorphophallus campanulatus*, *Dioscorea belophylla*, *D. oppositifolia*, *Ipomoea aquatica*, *Bamboos*

Leaves: *Agave americana*, *Aloe vera*, *Moringa oleifera*, *Antidesma diandrum*, *Fern species*

Edible Bamboo Shoots: *Bambusa balcooa*, *B. bambos* (Kanta bans/Spiny bamboo), *B. polymorpha* (Betwa), *B. tulda, B. nutans*, *B. pallida*, *Dendrocalamus asper*, *D. brandisii*, *D. giganteus* (Giant bamboo), *D. hamiltonii* (Kagzi bans), *D. longispathus*, *D. strictus* (Lathi bans/ Male bamboo), *D. latiflorus*, *D. oldhami*, *D. membranaceus*, *Phyllostachys pubescens*, *P. praecox*, *P. iridescens*, *P. bambusoides*, *P. edulis*, *P. dulcis*, *Schizostachyum*, *Thyrsostachys*, etc.

Fungi: *Agaricus campestris*, *Morchella esculenta*, *Volvaria terastius*, *Collybia albuminosa*

Canes/Rattan

The important species of cane are *Calamus acanthospathus*, *C. guruba, C. tenuis, C. viminalis, C. rotang, C. andamanicus, C. brandisii, C. flagellum, C. gambeli, C. gracilis, C. latifolius, C. pulstris, C. rheedei, Daemonorops kurzanius, Plectocomia himalyana.* Among these, *Calamus tenuis* is the common cane of north India.

Palms

Palms are important NWFP with numerous uses such as food, beverages, oil, fuel, feed, fertilizer, building material, furniture, games and toys, ornamental uses, medicinal uses etc. The important palm genus are *Areca*, *Arenga*, *Bentinckia*, *Corypha, Hyphaene, Licuala, Livistona, Loxococcus, Oncosperma, Phoenix, Pinanga, Wallichia, Caryota, Nypa* and *Borassus.*

The above mention list is indicative and includes the commonly used Indian plants but there are many more plants in the world used for food and survival. The proper screening of prioritized plants for their domestication/ introduction and utilization is necessary for future food security of the nation.

Agroforestry in Semi-Arid Regions

Agroforestry in the semi-arid tropics of India involves integrating trees with crops to improve food security, reduce income variability, and adapt to climate change. Key practices include planting fruit trees and bamboos, which provide economic benefits and have a higher resilience to drought. Challenges like stray animals, market access, and extension services need to be addressed through institutional support to expand these practices. Increasing tree density and diversity on farms has been shown to significantly increase food security. Agroforestry systems help stabilize farmer incomes, making them more resilient to climate and market fluctuations. Agroforestry is a climate-smart agriculture practice that is less vulnerable to climate variability and drought. Systems like bamboo-based agroforestry can provide higher financial returns compared to sole crops or sole bamboo, especially through products like wood

and crops like sesame and chickpea. Agroforestry practices such as farmer-managed natural regeneration save labor and help regenerate degraded land.
The land use management required in arid tract to focus on drought resilience; soil & water conservation; supplemental income and risk mitigation. In arid region this management system therefore, needs to be devised that is capable of producing food from marginal agricultural land and is also capable of maintaining and improving quality of producing environment have different perspectives in ecological, economic and social spheres. Diversification of the activities of arable farmers, with the building-up of an inheritance of multipurpose trees in ecological sequence adds with continuous revenue from farm. Tree species that are little used for industrial woods like timber, furniture, paper, plywood, etc., but are of high value NWFPs and provide ecological services, could be grown in agroforestry systems. NWFPs based agroforestry systems on croplands/farmlands bring significant economic return even in incidence of total crop failure, common to single-cropping also incomes due to improved and sustained productivity. Besides the economic benefits, social benefits occur from increase in products for nutrition and health. It provides rural and poor farm communities an improved and sustained livelihood.

Non-Wood Forest Products Based Agroforestry

The farmers and land owners integrate a variety of woody perennials in their crop and livestock production fields depending upon the agroclimates and local needs for diversified products. With the current interests in agroforestry worldwide, attempts are being made to introduce agroforestry techniques using indigenous and exotic multipurpose and nitrogen-fixing woody perennials. Agroforestry is widespread in all ecological and geographical regions of tropical regions. The systems vary enormously in their structural complexity and species diversity, their productive and protective attributes and their socio-economic dimensions. They range from apparently simple forms of shifting cultivation to complex homegardens; from systems involving sparse stands of trees on farm lands (e.g. *Prosopis cineraria*) to high-density complex multistoried homesteads of humid lowlands; from systems in which trees play a predominantly 'service' role (e.g. shelterbelts) to those in which they provide main salable products (e.g. intercropping with plantation crops).

The International Conference on Domestication and Commercialization of Non-Timber Forest Products in Agroforestry Systems, hosted by ICRAF, was held in Nairobi, Kenya, from 19 to 23 February 1996. This was the first world-level meeting to be held exclusively to draw attention to issues dealing with domestication and commercialization of non-timber forest products in agroforestry systems. The programme "Promotion and Development of Non-Wood Forest Products (NWFP)" at the Forest Products Division of FAO's Forestry Department, aims to enhance the value of non-wood forest products and services through improved harvesting, utilization, trade and marketing. Incorporating NWFPs in production systems is not a new practice. Various forms of agroforestry associations have developed around NWFPs and form the very basis of a suitable indigenous agriculture. It is only in recent years that agroforestry research is considering the prospects of these indigenous systems for forest species. In Southeast Asia, a complex agroforestry system for the management of forest resources have been developed for centuries by local people ranging from the production of locally consumed fruits to highly valuable industrial products, such as resins and latexes. These agroforestry systems are transformations of both selected forest resources and a true forest structure from the sphere of 'nature' to that of 'agriculture'. This process can thus be analyzed as a particular domestication strategy, which could integrate conventional species domestication techniques: selection, reproduction and plantation practices; to an original form of ecosystem 'domestication'. Prospects for further developing this agroforest strategy for the domestication of forest species, particularly NWFPs, are very important. The social, economic and institutional implications of such an integration of NWFP resources to agricultural development are to be analysed, based on various examples of agroforest development and focusing on the efficiency of this 'appropriation' strategy by smallholder farmers.

Forestry definitively needs to find an answer to the exhaustion of wild resources while in the same time rationalizing the production of marketable NWFPs. There is great demand for new crops and new markets which can be meeting out by integrating it in food forest system in agricultural landscape. Sustainable development has to mitigate the effects of deforestation by increasing the planting of trees on cleared lands, and farmers have to find substitutes for the natural resources lost through deforestation. Farmers' work of trials and tests tends to develop a range of food crop varieties and decades of agroscientific research to create productive clones of industrial tree crops. Modern agricultural and forestry science has to look harmonious alliance in development agroforestry models with these NTFPs for not only crop diversification but also for productivity enhancement. The domestication of natural resources involves a move from gathering in the wild on communally owned land to the deliberate cultivation of NWFPs on tenured farm land. The domestication of a chosen species then involves genetic selection and the management of varieties or cultivars. Through selection, yield and quality are improved so that the price paid for the product increases. There are however several constraints to domestication and the formal development of markets for NWFPs which includes-

- Lack of infrastructure in the rural areas, making access to markets difficult
- Low volume of products
- Poor or variable quality of products
- No continuity of supply
- Poor handling and storage qualities
- Limited knowledge of the product among consumers

One group of NWFPs with commercial potential is the essential oils. For example, when Israel tried to break into the geranium oil industry, it obtained its germplasm from France, which is a top producer. Similarly, South Africa, it was found that *Tagetes minuta* oil had characteristics that the market needed, although continuity of supply was difficult to guarantee without its cultivation and also farmers preference for crop substitution. The design of the agroecosystem in which domesticated species are grown is as essential as the choice for particular plant selection, breeding and reproduction techniques. This is particularly important when switching from annual crops to trees and from fields to forests. Even in agroforestry models are either fuel-based, fodder-based or industrial wood based intensive e.g. eucalyptus and poplar tree models with wheat or rice in northern India. However, other available models exist, which should be examined under the new perspective of domestication of NWFPs of forest species, particularly in agroforestry. It is essential to understand that the importance of an ecosystem approach to domestication goes far beyond biological or technical considerations. It is essential to analyze in the context of NWFPs domestication, as it deeply linked to forest communities and their socioeconomic life. Domestication is part of a resource appropriation process by a powerful fraction of the population. Agroforestry is recognised as a promising land-use technology and an interface between agriculture and forestry, especially in the developing countries of the tropics and subtropics. With recent research, the principles underlying age-old agroforestry practices are gradually being understood, and improved practices are introduced. The scientific foundation of agroforestry is the multipurpose tree (MPT). Two important attributes of MPTs are their ability to produce multiple products, from one or more plant parts, and their ability to provide benefits and services that may be intangible but nonetheless environmentally significant. Very little has been done to exploit the non-wood forest products (NWFPs) in agroforestry systems. Considering that agroforestry places a strong emphasis on smallholder, low-input, multiple-output systems and many of the trees and other species that produce NWFPs are amenable to integrated management, agroforestry as a land-use approach and NWFPs as an output are closely integrated. Many MPTS are also provide non wood products other than timber, fuel and fodder. Agroforestry and NWFP extraction are predominantly subsistence practices; they make minimal use of costly external inputs, but heavy use of human labour; and each has location-specific characteristics. However, there are also subtle differences between NWFP production and the practice of agroforestry. First, agroforestry systems are, generally, more intensively managed, with a higher degree of species domestication, than most NWFP species. Second, agroforestry systems place emphasis on not only the productive role of their woody components, but also of their protective roles such as soil amelioration and environmental protection. This need not necessarily be so in the case of NWFP species. A third difference is that although agroforestry is often described as an interface between agriculture and forestry, most agroforestry practices are on the so-called agricultural and marginal lands and some in the buffer zones around forests, with very little or no agroforestry in the forests. NWFPs, with some notable exceptions are extracted mostly from forest and/or marginal land, with relatively lesser quantities from agricultural lands. Identification of such similarities and contrasts between common agroforestry practices and NWFP extraction can help in examining opportunities for integrating NWFPs and agroforestry systems. By placing NWFPs in a production system context, this may also help to explore new benefits of NWFP species (Nair 1995). The possible impacts of NWFPs based agroforestry are:

- Poverty alleviation through increased income by diversifying the production of agroforestry products for home consumption and market.
- Nutritional security by incorporation of wild fruits, vegetables, nuts, spices, herbs etc NWFPs with traditional agricultural cereal and millet crops.
- Empowerment to women farmers and small holdings rural residents in processing and value addition of NWFPs through development of rural units.
- Checking irrational harvest and pressure on forest by providing NWFPs on farms.
- Increasing buffering capacity of farmers against the climate change and participation in carbon trading.
- Development of rural small scale and cottage units based on diverse NWFPs through cooperatives.
- Augmenting accessibility to medicinal plants for primary health care and revitalization of local health traditions.
- *Ex situ* conservation / domestication of lesser known plants in farm for the future improvement of these crops.

- Improving the agrobiodiversity *vis-a-vis* ecological sustenance of the agroecosystem and control of insect-pest.
- Blending of ethno-agriculture with modern agrotechniques for commercialization of NWFPs from agroforests.

Like any other agroforestry practices NWFPs based agroforestry is also intentional systematic combinations of trees, shrubs, herbs with crops and/or livestock that involve intensive management of the interactions between the components as an integrated agroecosystem. It also satisfies the criteria of Intentional, Intensive, Interactive and Integrated approach for wider adoption and production. The minor demarcation only that it emphasizes more on adoption for poverty alleviation and rural development of small and marginal farmers rather intensive production by large farmers for selected NWFPs. It provides a different land use option, compared with traditional arable and forestry systems. It makes use of the complimentarily relationship between trees and crops in vertical strata, so that the available resources can be effectively utilized. It is a practice that supports the environment and has an obvious landscape benefit. It allows for the diversification of farm activities and makes better use of environmental resources. Domestication of agroforestry trees for non-wood tree products (NWTPs) requires information on yield data, selection criteria, botanic knowledge and consumer acceptance. The tree species that provide NWTPs have the primary purpose of enhancing the productivity and sustainability of agroforestry systems. It is further desired that conserved germplasm in these landscapes the provision of improved germplasm will accelerate adoption and expansion of agroforestry technologies. FAO (1995) lists advantages and disadvantages of the domestication of NWTPs. Advantages include reliable production, relieving pressure on forests, income generation, ease of harvesting, improved growth rates, increased value of the crop. The disadvantages focus on increased susceptibility to pests, loss of ecological function, reliance on new sources of wild seed, added-value benefit to large corporate entities. The development of new tree crops on a sufficient scale in sustainable agroforestry systems is a challenge to link genetic improvement research with marketing to ensure income generation and food security. Agroforestry systems where NWTPs trees could play a role are numerous and include homegardens, scattered trees in fields, multistrata systems and boundary plantings. Agroforester needs to ascertain whether it is likely that there will be a market for its products, while the industry that develops the market wants to know that there is a minimum reliability of supply for a uniform product of a given quality, before committing capital to developing that market. Nevertheless, some progress has been made in thinking about the impact on small-scale, resource-poor farmers of domesticating and commercializing NTFPs.

Non-Wood Forest Products Based Agroforestry in Arid tracts

In these regions, Non-Timber Forest Products (NTFPs) such as gums, resins, fruits, seeds, fibers, and medicinal plants contribute significantly to household income and resilience. NTFP-based agroforestry systems integrate woody perennials with crops/livestock and help diversify income while enhancing ecological sustainability. The NWFP based agroforestry systems can be adopted in any type of traditional and modern agrofoestry systems by integration of components and modification in spatial and temporal arrangement.

1. Trees on Farm-boundaries: Multipurpose trees mainly for fruits and other products can be grown on farm boundaries. In northern parts of India, Jamun (*Syzygium cuminii*), Ber (*Ziziphus* spp.*),* Lasora (*Cordia myxa*), *Morus alba*, *Azadirachta indica, Acacia Senegal*, *Borassus*, bamboo (*Dendrocalamus*, *Bambusa*), etc. all along the irrigation channels. In Andamans, farmers grow *Gliricidia sepium*, *Jatropha* spp., *Ficus* spp.*, Ceiba pentandra*, *Vitex trifolia* and *Erythina variegata* as live hedges. At many places succulents like *Agave* and many cactoids are grown as common live-fence.

2. Forest/ Ecological Farming: The use of farm woodlots and fringe forest areas by farmers for obtaining Non timber products such as herbs, sugar, honey and food has been historical other than woods. Mostly in tropical areas is common but arid tract alos ahs potential with Custrad apple, Karonda, pomegranate, Jungali jalebi , moringa, and various shrubs, cactus, wild vegetables to form homesteads/ forest farming sub system for round the year collections.

3. Parkland systems

It is the most widespread system of agricultural production. Trees are present everywhere on the farmers' fields. Trees of useful species are selected in fallow land for retention, before bringing the land into cultivation. Thus, tree regeneration is the result of the practice of fallowing. The main reason for maintaining woody species in the fields is the demand for food and traditional medicines, for both humans and animals. These products, which are currently undervalued, contribute to the enhancement of the nutrition of rural populations, a better family income (particularly for women) and the economy of the country. **Scattered Trees:** Trees are grown scattered in agricultural fields for many uses such as shade, fodder, fuel wood, fruit, vegetables and medicinal uses. The parkland system, characterized by mature trees dispersed in cropped fields, is the largest single agricultural land use in sub-Saharan

Africa and Asia as well. It is quite possible that some of these older parklands are remnants of elaborate pre-colonial agricultural systems, with cropping intensities and input levels not found in the region today (Hervouet, 1991). The ability of these parklands, or two tiered systems, to enhance and stabilize crop production has been much studied over the past 30-40 years in arid parts of globe. The systems that have received the most attention are the *Prosopis cineraria*/millet mixtures of eastern Rajasthan, India (Mann and Saxena, 1980), and the *Faidherbia albida*/grain systems predominating throughout the Sahelian zone and in some parts of East Africa. This system provided soil fertility, crop cultivation and climate resilient production system in current scenario. Given the high microsite variability in many SAT soils, an alternative strategy may be to identify "islands of fertility" in farmer's fields and plant locally favoured species on them. The subsequent rapid growth and high survival rate would be attractive to farmers and would lessen the amount of time needed to protect small young trees. Another possible option would be to introduce more valuable cash crops in the favourable microenvironment found under the shade of existing mature *F. albida* or *P. cineraria* trees.

4. Shelter belts or Wind-breaks/ Bamboo brackets (Green belts or walls in agrilandscapes for NTFP protection)

Tree rows as wind-breaks have long been used in semi-arid temperate regions of North America, Europe and Asia for protecting crops and soil against wind damage and wind erosion. More recently, their effectiveness in increasing crop production has been demonstrated in the drier parts of the SAT, particularly sub-Saharan Africa. The few critical studies that have been done in the SAT confirm findings of increased crop yield behind wind-breaks in semi-arid temperate regions. Wind-breaks / shelter belts in many of the projects were designed to run in straight lines perpendicular to damaging winds in larger landscapes not in small farmers lands. The species may be chosen as per locality MPTs and tolerant like *Acacia nilotica, A. catechu, Eucalyptus camaldulensis, Dalgergia sissoo, Leucaena leucocephala, Causarina equistifolia*. Further research into the ecophysiological processes, favourable and unfavourable, that govern wind-break/crop interaction in the SAT is important. Bamboo-based systems, such as combining *Dendrocalamus strictus* with crops like sesame and chickpea, are well-suited for drought-prone areas. Bio fencing is integral part of farming system in arid tracts

5. Alley cropping & Agrisilviculture

Based on positive results from the humid tropics, particularly at the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria, alley cropping has generated much interest in Africa and Asia. It is widely adapted by farmers in West Africa, particularly in Sudanian zone now allows extensive animal husbandry. The fodder needs of these animals will compete with the use of hedgerow loppings for green manure, a key component of the alley cropping technology. Narrow hedgerows, spaced at distances recommended for the humid and sub humid tropics (i.e. 4 m), are particularly competitive with crops in the SAT probably because of underground competition for water. Despite these limitations, the concept of carefully placed and closely pruned rows of trees in farmers' fields may have a role to play in SAT farming systems and in suitable contour intervals may serve to protect highly erosive soils. In established Agrisilviculture systems, crops that can tolerate shade or have shallow root systems can be grown between trees. Farmers also cultivate a variety of crops such as pulses, groundnut, sunflower, and some vegetables within agroforestry systems.

6. Silvipastoral/ Horti pastoral systems

There are many animal husbandry systems in the SAT, but two extremes may be recognized. The first is where animals are a permanent fixture in the farming system (as in much of India), and are primarily stall-fed with supplemental pasturing. The other extreme is the nomadic and transhumant systems of the Sahel, where animals are moved from one site to another according to changing pasture conditions throughout the year, or herded to distant pastures during the rainy season to protect crops. In both cases, livestock play an important role in sustaining field fertility through manure production. In India, farmyard manure is normally collected and spread on the fields. In the Sahel, herders are paid to bed animals on arable fields.

In both systems, livestock pressure must be balanced with rangeland vegetative productivity if it is to be maintained. Under communal ownership, the incentive is to expand one's herd, without concern for the effect it has on the land, in order to reap maximum short-term personal gain. At the same time, the long-term impact of such individual misuse is shared by all users, and therefore the individual's long-term loss is buffered. The usefulness of fitting the potentially excellent feeding value of SAT trees and shrubs into pastoral and agropastoral systems. It is possible to think of all sorts of grass/tree/crop designs to produce more fodder at the farm level, there are suitable fodder trees and other suitable perennial vegetation components of almost every agroforestry system for the SAT. Overall direction of research and development work at the farm level in this area should be the designing of efficient cut-and-carry systems.

7. Miscellaneous systems

Where irrigation is available, or in river valleys where water-tables are close to the soil surface, many traditional agroforestry systems closely patterned after those in the humid tropics can be observed. In non-irrigated areas, tree planting for specific farm management objectives is little studied but of significant potential. Vegetative fences either live or in the form of thorny prunings, are widely used in the SAT. Similarly, boundaries between fields and farms could be made productive by tree or shrub planting for browse and other uses. Trees can play an important part in river and stream bank and waterway stabilization efforts, vegetative contour strips for soil conservation and simply for shade.

Examples of some NTFP cum functional system

a. Tree–crop boundary systems: *Ziziphus mauritiana* (ber), *Azadirachta indica* (neem) grown on field boundaries — fruits/seeds + pest control/soil benefits. (ber+legume interplanting)

b. Gum & resin systems: *Acacia senegal* (gum arabic), *Boswellia serrata* (salai/Frankincense family), *Commiphora* spp. for resin/gums — tapped/collected and sold or processed locally.

c. Fruit & processing systems: Based on fruit trees like mango, sapota, and guava are popular and have been found to be profitable. Aonla orchards integrated with seasonal crops — fruits processed to candies/powder/juice (value addition).

d. Silvopastoral systems: Fodder trees (e.g., *Prosopis*, *Hardwickia*) with grazing — supports livestock + fodder NTFPs.

e. Homegardens & MAPs: Small plots near homes with *Withania*, Aloe, herbs for household use and local market sale

f. Livelihood resilience: NTFPs give seasonal cash during lean agricultural periods and provide daily subsistence (food, medicines), especially for landless and women collectors.

h. Market/value-chain upside: Processing (gum cleaning, fruit drying, oil extraction), product standardization, FPO/SHG aggregation and branding (e.g., fair-trade, medicinal extracts) substantially raise returns vs raw sales.

g. Ecological benefits: Trees on farms improve soil organic matter, reduce erosion, increase water infiltration, and support biodiversity and carbon sequestration — agroforestry systems can reach a high share of natural forest biodiversity.

Examples of NTFP based Agroforestry from specific arid regions

In Bundelkhand region agroforestry is a crucial climate-smart option here, with fruit-based and bamboo-based systems showing high potential. Similarly in other arid region shows a significant correlation between landholding size and tree density, with a diverse range of trees and crops being cultivated. Agroforestry is being promoted for land restoration and carbon sequestration, with efforts focused on plantation, farmer support, and policy reform. In southern region of India like Karnataka it involves integrating trees with agriculture and livestock to enhance productivity and resilience, especially in regions with limited rainfall. Common practices include alley cropping, silvopasture, and incorporating drought-resistant trees like neem, tamarind, and acacia into farming systems, providing shade, improving soil health, and generating additional income from tree products.

In Bundelkhand traditional practices involving NTFP collections from trees like *Acacia nilotica* (babul), *Acacia catechu* (khair), *Butea monosperma* (palas), Mahua (*Madhuca indica*), Tendu leaves (*Diospyros melanoxylon*), Neem, Aonla (*Emblica officinalis*), Ber (*Zizyphus varieties*) and other wild fruits/medicinal plants. Substantial household dependence (many villages report 40–60% households engage in NTFP collection) and NTFPs often supply **~25–35% of seasonal household income** in poorer seasons but from natural or common lands not from farms. Modern agroforestry can be beneficial for the region, which has unique soil types and faces challenges like drought, by integrating trees with crops and livestock. Similarly for emerging challenges of degraded landscapes invites intervention for soil improvement by integrating trees helps improve soil structure, particularly in the region's coarse-grained loam and clayey soils, and can reduce erosion. Planting high-value trees like teak (though long-term) or faster-growing options like poplar or eucalyptus can provide additional income streams.

NTFP Species planted on field boundaries or in silvipastoral systems: *Acacia Senegal-* Gum Arabic-Industrial, medicinal; *Acacia Senegal-* Gum Arabic-Industrial, medicinal; *Boswellia serrata* -Salai Gum-Pharmaceutical, incense; *Commiphora wightii* – Guggul-Ayurvedic; *Ziziphus mauritiana* - Ber fruits- Food, processing; *Prosopis cineraria* –Pods- Fodder, food supplement; *Azadirachta indica* -Neem seeds/oil- Pesticide, medicinal, *Balanites aegyptiaca-* Nuts, oil- Food, cosmetics

Horti-Pastoral & Horti-Agroforestry Systems-Ber-based systems with legumes → fruits + fodder + soil fertility; Aonla-based systems → fruit + processing potential NTFP-Oriented Homegardens- Limited in SAT, but provide: Medicinal plants (Aloe vera, *Withania somnifera*), Spices, seeds, fruits

Constraints in promotion of NTFPs based Agroforestry

Information on the quantity and value of NWFPs are either non-existent or unreliable and most are estimates. Considering that NWFPs represent a hitherto ignored area of scientific and academic interest, this state of affairs is not unexpected. Because of the descriptive nature of most NWFPs and agroforestry literature, it is difficult to make a quantitative assessment of the extent of NWFPs use in agroforestry systems. ICRAF's global inventory of agroforestry systems during the 1980s, which provides the most comprehensive account of agroforestry systems in developing countries, lists 380 perennial woody species reported as components of existing agroforestry systems and their main uses in different regions. Most of the available reports describe systems where NWFP-yielding plants are grown in association with commercial tree crops. Avilable literature identifies a number of localized, under-exploited tree species that produce NWFPs in a variety of ecosystems and outline the potential for their improvement through agroforestry. NWFPs have a major role in many indigenous agroforestry systems; and agroforestry offers a viable approach to realizing the potential of several under-exploited NWFPs. Chandrasekharan (1993) has identified a large number of issues related to the development of NWFPs and suggested that nothing goes right or proper for NWFPs at the present time. Inventory of NWFPs - A serious hindrance to NWFP development is the lack of authentic and reliable statistics on the classification, production, and value of NWFPs. Product grouping followed in statistical reports and the aggregation of products in International Standard Trade Classification (ISTC) makes it impossible to separate out NWFPs by specific products and sources. Many NWFPs fall under the category of "vegetable materials and vegetable products".

Conclusion

Agroforestry has made tremendous strides in recent years, but many challenges remain in terms of its wider application. It is necessary to identify and measure the range of benefits, given that they are not well documented. The limited success of many agroforestry development projects has been due to overambitious expectations on the pan of those planning such programmes. Better results will be obtained when agroforestry is seen as merely one of the many tools available to agriculture and forestry development workers and researchers. For maximum success, agroforestry technologies should be addressed to a limited range of problems and products, and in the future must be designed to mesh closely with local farming realities, needs and constraints. The forestry aspect of the discipline must stress that a given tree species, like any other plant species, has specific site requirements. Moreover, additional research is required to quantify the benefits to various stakeholders, to deal with the variability in benefits, to assess the effects and trade-offs of different policies and to examine the impact of agroforestry practices on forest protection, particularly in the tropics. Measures are required to overcome lack of planting materials (seeds, seedlings or cuttings) and lack of information. Improving marketing and adding value to raw products are critical for enhancing the livelihoods of agroforestry farmers. Community based institutional mechanisms are needed to help farmers acquire information and business skills, market produce and promote quality. The resource-poor farmers of the tropics plant trees that provide NTFPs for a variety of reasons (food, income generation, risk aversion through diversification). Fitness of purpose of agroforestry trees is the prime objective of domestication, and this is best ensured through provision of a choice of priority species to farmers.

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Industrial Agro-forestry: Opportunities and Challenges

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Introduction

Before the Forest Conservation Act and National Forest Policy were passed in 1988, forests were the primary source of raw materials for the majority of the wood industry. With declining raw matter availability for various wood-based industries, they want to shift alternate supply of raw material. However, Forest conservation Act and National Forest Policy (1988) directing all the forest-based industries should become self-reliant in raw material production and must source materials from outside forest areas by collaborative models such as industry farmer's linkages, contract farming, and buy back agreements (Durairasu et. al., 2014). Additionally, the Hon'ble Supreme Court of India's 1996 judgement outlawed the uncontrolled felling of trees and timber logging in government forests (Ghosh et. al., 2016). In this context, Industrial agroforestry offers a sustainable and economically viable pathway. It enables farmers to cultivate industrially important tree crops on agricultural land either as pure block plantations or integrated with crops thereby producing raw materials while also maintaining food security. This system maximizes land productivity, strengthens rural livelihoods, and reduces pressure on natural forests (Manikanandan & Prabhu, 2016).

Industrial agroforestry became an emerging land-use system that integrates commercially valuable tree species with agricultural crops or cultivated land to meet the raw material requirements of forest-based industries. Traditionally, forests supplied timber, pulpwood, fuelwood, latex, resins, and other industrial raw materials. However, with production forests rapidly shrinking and strict conservation mandates limiting extraction, industries are now facing severe raw material deficits (Parthiban & Fernandaz, 2017). Unlike traditional agroforestry, which primarily aims at subsistence, ecological restoration, and diversified farm income, Industrial agroforestry is designed to meet commercial-scale demand through planned plantations, contract farming, and value-chain integration. Industrial agroforestry refers to the strategic cultivation of tree species on farmland to supply raw materials for industries such as pulp and paper, plywood, furniture, bioenergy, natural resins, pharmaceuticals, and other value-added products.

Industrial agroforestry bridges the critical gap between rising industrial demand and shrinking forest supply while ensuring ecological stability and economic viability. There are some key reasons for its growing importance:

- Shrinking forest resources leading to poor availability of industrial wood. Increasing demand for pulp, paper, furniture, plywood, and medicinal products.
- Competition for agricultural land where farmers require high-value options without compromising food production.
- Need for climate-resilient land-use systems due to changing environmental conditions.

Major Industrial Agroforestry Models

Industrial agroforestry systems often rely on partnerships between farmers, industries, and state agencies, facilitating assured markets, improved technologies, and extension support.

Table 1. Industrial important tree species with prominent key features

Sr. No.	Species	Industrial Use	Key Features
1	*Casuarina*, *Eucalyptus*	Pulp & paper	Fast-growing, clonal propagation
2	*Ailanthus excelsa*	Matchwood	High-quality, straight-grained wood
3	*Ficus elastica*	Rubber	Used by state rubber corporations
4	Teak, Mahua, *Terminalia*	Timber	High market demand
5	Mango, Poplar, Semal	Plywood	Widely used in plywood mills
6	*Terminalia elata*	Sericulture	Used for wild silk (tassar)

Opportunities in Industrial Agroforestry:

Economic Opportunities

- **Enhanced and diversified income:** Farmers earn from both agricultural crops and industrial wood, creating multi-year revenue streams.
- **Assured markets through contract farming:** Many industries provide buy back agreements, reducing market risks.
- **Employment generation:** Nursery raising, harvesting, transportation, and value addition create jobs in rural areas.
- **Reduced dependence on forest resources:** By supplying industrial wood domestically, agroforestry decreases the need for imports.

Environmental Opportunities

- **Carbon sequestration:** Industrial tree plantations capture significant carbon, contributing to climate change mitigation.
- **Soil conservation:** Tree cover improves soil structure, organic matter, and microbial activity.
- **Water regulation:** Trees enhance infiltration and reduce surface runoff.
- **Biodiversity enhancement:** Agroforestry landscapes support birds, insects, and beneficial soil fauna.
- **Climate resilience:** Trees buffer agricultural crops against extreme temperatures and wind.

Technological and Institutional Opportunities

- **Improved planting materials:** Clonal varieties of *Eucalyptus*, Poplar, *Casuarina*, and *Melia dubia* offer higher productivity.
- **Mechanised operations:** Modern planting, harvesting, and processing tools improve efficiency.
- **Government policies:** National Agroforestry Policy (2014), state felling relaxations, and subsidies support expansion.
- **Industry farmer partnerships:** Collaborative models enhance extension, logistics, and field-level capacity building.

Social Opportunities

- **Rural empowerment:** Increased income and resource generation strengthen rural economies.
- **Women's participation:** Nursery management, value addition, and post-harvest activities open livelihood avenues.
- **Skill development:** Training in silviculture, agroforestry management, and processing enhances rural skill sets.

Challenges in Industrial Agroforestry

Economic Challenges

- **High initial investment:** Costs for land preparation, quality planting materials, and maintenance may be prohibitive.
- **Fluctuating market prices:** Wood prices may vary intermittently, affecting profitability.

- **Delayed returns:** Tree crops involve multiyear gestation periods, making them less attractive to small and marginal farmers.

Environmental Challenges

- **Water consumption of certain species:** Some species like *Eucalyptus* and Poplar are often perceived as high water users.
- **Monoculture risks:** Large-scale monocultures may reduce biodiversity and increase vulnerability to pests.
- **Soil nutrient mining:** Fast-growing species may deplete certain nutrients if unmanaged.

Institutional and Policy Challenges

- **Regulatory hurdles:** Felling and transit regulations vary by state, causing confusion.
- **Weak extension services:** Lack of field level technical guidance limits adoption.
- **Limited credit/funding**: Financing long rotation plantations is less common in banks.
- **Inadequate value chain infrastructure:** Transport, storage, and processing units may be located far from farms.

Technical Challenges

- **Poor-quality planting material:** Uncertified seedlings lead to low productivity.
- **Pest and disease vulnerability:** Industrial species like *Eucalyptus* may face canker, wilt, and defoliators.
- **Lack of mechanization:** Harvesting and transportation are often labour intensive.

Strategies to Enhance Industrial Agroforestry

Strengthening Farmer–Industry Linkages

- Promote contract farming and buy back agreements.
- Establish cluster-based models and farmer producer organizations (FPOs).

Policy and Institutional Interventions

- Simplify and harmonise felling/transit rules across states make it uniform throughout India.
- Provide financial incentives, subsidies, and insurance to the farmers for tree crops.
- Strengthen extension systems through Krishi Vigyan Kendras (KVKs), state forest departments, and NGOs.

Technological Improvements

- Promote clonal and genetically improved planting materials.
- Adopt precision irrigation, fertigation, and mechanised harvesting.
- Encourage multi-species, climate-resilient plantations.

Environmental Safeguards

- Integrate species that balance water use and ecological benefits.
- Promote mixed plantations over monocultures.
- Encourage soil nutrient management plans.

Market and Value-Chain Enhancements

- Develop local processing units for timber and plywood and other cottage industries.
- Create digital platforms for marketing, pricing, and logistics.
- Train farmers in value addition and commercial-grade harvesting.

Conclusion

Industrial agroforestry presents a transformative opportunity for sustainable rural development, climate mitigation, and industrial growth. By combining ecological stewardship with commercial value chains, it offers a win-win pathway for farmers, industries, and the environment. However, realizing its full potential requires addressing challenges related to market fluctuations, regulatory barriers, environmental concerns, and technical capacity. Through strengthened farmer industry linkages, policy reforms, technological advancements, and sustainable land management, Industrial agroforestry can emerge as a key pillar of future green economies.

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Strengthening Agroforestry through Targeted Extension Approaches

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Introduction

Agroforestry, as a land-use system that harmonizes agricultural productivity with ecological sustainability, holds immense potential to address pressing challenges such as land degradation, biodiversity loss, and rural poverty (Irwin et al., 2023). Despite its well-documented benefits and centuries-old roots in traditional farming systems, agroforestry has yet to achieve widespread institutional integration or farmer adoption at scale. This shortfall can largely be attributed to structural and systemic limitations within the extension and policy environment (Houndjo Kpoviwanou et al., 2024; Sharma et al, 2025). The following key barriers illustrate the multifaceted challenges that hinder the effective promotion and implementation of agroforestry:

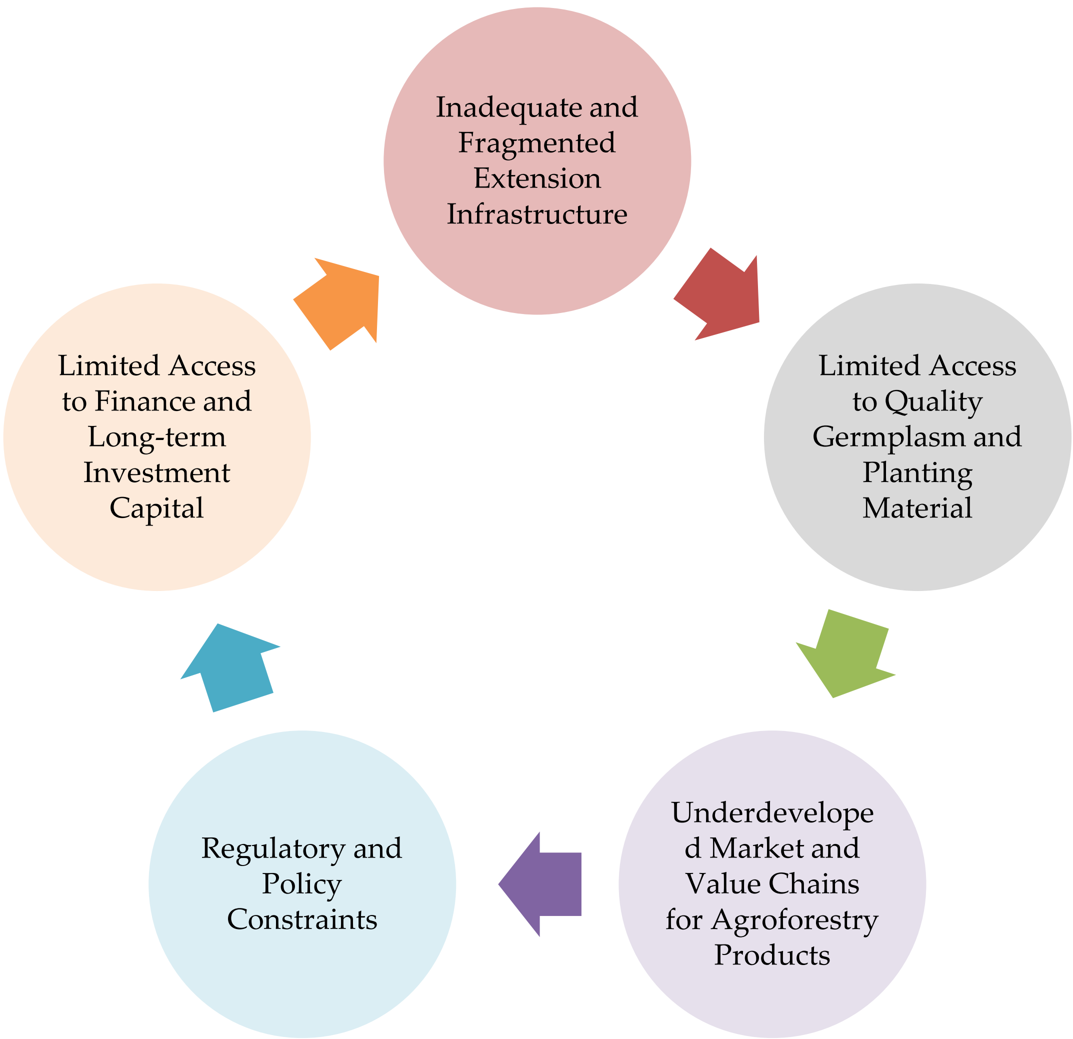

Figure 1. Key barriers hindering the effective promotion of agroforestry

Inadequate and Fragmented Extension Infrastructure

One of the foremost constraints to the scaling up of agroforestry is the lack of a dedicated, well-structured, and capacitated extension system. Unlike conventional agriculture, where extension mechanisms are relatively well established, agroforestry remains marginalised, falling between the mandates of agriculture and forestry departments. This institutional ambiguity leads to fragmented support, with extension activities often limited to the distribution of seedlings or ad hoc awareness campaigns, rather than sustained technical and advisory services tailored to site-specific agroforestry systems. Furthermore, the multidisciplinary nature of agroforestry, which spans agronomy, forestry, ecology, and socioeconomics, requires an integrated extension approach, which is currently lacking in most public extension systems.

Limited Access to Quality Germplasm and Planting Material

Another significant bottleneck is the poor availability of high-quality, certified planting material, especially for indigenous and underutilised tree species. Tree seed systems are underdeveloped, and existing nurseries frequently lack both technical capacity and regulatory oversight to ensure genetic quality and species suitability. In many regions, farmers rely on informal sources of germplasm, which may be poorly adapted or of inferior quality, ultimately compromising productivity and ecosystem benefits. The situation is further compounded by the limited investment in research and infrastructure for the multiplication and dissemination of elite planting material tailored to different agro ecological zones.

Underdeveloped Market and Value Chains for Agroforestry Products

Market incentives play a critical role in farmer decision-making. However, the commercial viability of agroforestry systems is often undermined by the absence of robust value chains for most non-timber agroforestry products. While certain commodities such as cocoa, coffee, and rubber have established markets, the same cannot be said for fruits, medicinal plants, nuts, resins, and other ecosystem-based outputs that could enhance livelihoods. The absence of organized producer groups, processing units, market intelligence, and reliable buyers limits the profitability of agroforestry enterprises, thereby reducing farmers' motivation to invest in tree-based systems (Irwin et al., 2023).

Regulatory and Policy Constraints

Despite policy-level recognition of agroforestry's potential, evident in instruments such as national agroforestry policies, implementation remains impeded by restrictive legal frameworks (Ssemaganda et al., 2024; Irwin et al., 2023). In many jurisdictions, cumbersome procedures and unclear regulations govern the harvesting, transport, and sale of tree products, even when trees are grown on private farmland. Such regulatory bottlenecks create disincentives for tree planting and discourage private investment in agroforestry, particularly for timber-producing species. Additionally, inconsistencies between national and subnational laws further exacerbate the challenge.

Limited Access to Finance and Long-term Investment Capital

Agroforestry systems typically require significant upfront investment and exhibit delayed economic returns, which may not align with the financial realities of smallholder farmers operating under subsistence or semi-commercial conditions. Access to suitable financial instruments, such as long-tenure, low-interest credit or risk-mitigating insurance products is extremely limited in rural areas. Traditional agricultural credit systems, which favor short-term lending cycles aligned with annual cropping, are ill-suited to the temporal dynamics of tree-based systems. Without targeted financial support, many resource-poor farmers are unable to bear the opportunity costs or risks associated with agroforestry adoption.

Table 1. Extension Approaches and frameworks to address the constraints in Agroforestry

Constraint	Extension Methods	Supporting Frameworks
Inadequate Extension	Farmers Field Schools (Krishivaniki Vidhyalaya), Digital tools, PRA	Pluralistic Systems, ICT4Ag
Germplasm Access	Seed banks, Demo plots	Value Chain Development, Integrated Seed Systems
Market Gaps	FPOs, Market linkage	Market System Development, Incubation Models
Regulatory Constraints	Policy literacy, Advocacy	Enabling Environment, Dialogue
Finance Access	Financial literacy, Result Based Financing	Climate Smart Agriculture, Investment Readiness

Inadequate Extension

Inadequate and fragmented extension infrastructure remains a major bottleneck in scaling agroforestry practices, particularly in rural and marginalized regions. To address this, several extension methodologies and frameworks have proven effective.

- **Farmer Field Schools (FFS) / Krishivaniki Schools:** It offer a participatory, hands-on learning environment where farmers collaboratively experiment with agroforestry techniques, enhancing local knowledge and peer-to-peer dissemination.
- **Digital extension platforms**: These platforms include mobile applications, SMS services, and online advisory tools bridge physical distance and allow for real-time, low-cost dissemination of agroforestry innovations.
- **Train-the-Trainer programs**: The approach build decentralized capacity by empowering lead farmers, community facilitators, and local NGOs to act as extension multipliers. Additionally,
- **Participatory Rural Appraisal (PRA)**: It ensures that farmers are actively involved in identifying their needs, constraints, and viable solutions.

These methodologies are best supported by the Pluralistic Extension System Framework, which integrates government, private sector, and civil society actors, and ICT4Ag, which promotes the use of digital tools to enhance outreach, access to information, and adoption of sustainable agroforestry practices.

Germplasm Access

Limited access to quality germplasm and planting material poses a significant constraint to the successful adoption of agroforestry systems. To overcome this, extension approaches focus on empowering farmers to produce and access reliable planting materials locally.

- **Community seed banks and nurseries**: They are managed by farmer groups or cooperatives, play a critical role in ensuring the availability of diverse and context-specific tree species.
- **Demonstration plots:** They act as effective visual tools to showcase the performance, resilience, and benefits of improved agroforestry species, encouraging wider adoption.
- **Public–Private Partnerships (PPPs)**: Extension services can link farmers with certified seed producers and private nurseries to ensure quality and scale.
- **Quality assurance training:** Training equips nursery operators and farmers with knowledge on seed selection, handling, certification standards, and nursery management practices.

These efforts are supported by the Value Chain Development (VCD) framework, which links germplasm supply to end markets, and the Integrated Seed System Framework, which connects formal and informal systems to enhance both accessibility and quality assurance.

Market Gaps

Underdeveloped markets and weak value chains significantly hinder the profitability and scalability of agroforestry systems. To address these challenges, extension services must go beyond technical training and focus on enhancing farmers' market engagement and entrepreneurial capacity.

- **Market linkage facilitation:** It plays a crucial role by organizing buyer-seller interactions, promoting contract farming arrangements, and introducing digital platforms for e-marketing of agroforestry products.
- **Enterprise development training:** Equips farmers with skills in value addition, including processing, packaging, branding, and pricing strategies that improve product competitiveness and shelf appeal.
- **Collective action through Farmer Producer Organizations (FPOs):** Promoting FPOs helps smallholders aggregate supply, access inputs at lower costs, and negotiate better prices, thereby strengthening their position in the value chain.

These approaches are anchored by the Agroforestry Business Incubation Model, which nurtures community-based enterprises and startups, and the Inclusive Market Systems Development (MSD) framework, which addresses systemic barriers to market access and fosters long-term, sustainable participation of smallholders in agroforestry markets.

Regulatory Constraints

Regulatory and policy constraints remain a critical barrier to widespread agroforestry adoption, often due to unclear land tenure rights, complex tree harvesting regulations, and limited farmer awareness of legal provisions. To overcome these barriers, extension methodologies must prioritize farmer empowerment and policy engagement.

- **Policy literacy campaigns:** Essential for educating farmers about land use laws, tree ownership rights, and environmental regulations, enabling them to make informed decisions and avoid legal complications.
- **Advocacy and stakeholder dialogues:** Create spaces for interaction between farmers, policymakers, and civil society to discuss challenges and propose reforms, thus ensuring policies are more inclusive and farmer-friendly.

- **Legal aid clinics for farmers:** It offer practical support on obtaining permits, clarifying land titles, and navigating regulatory processes related to tree planting and harvesting.

These approaches align with the Enabling Environment Framework, which aims to identify and remove legal and institutional bottlenecks, and the Public–Private Dialogue Framework, which encourages multi-stakeholder collaboration for effective policy implementation and reform.

Finance Access

Limited access to finance and long-term investment capital is a major obstacle that restricts farmers from adopting and scaling agroforestry systems, which often require upfront investments and have longer return periods. To address this, targeted extension approaches are essential in building farmers' financial capacity and connecting them with appropriate funding sources.

- **Financial literacy and business planning training** equip farmers with the skills to develop viable agroforestry enterprises, including preparing bankable project proposals and managing cash flows.
- **Linkages with microfinance institutions (MFIs):** Facilitating and promoting the use of cooperatives and self-help groups (SHGs) helps improve access to credit and reduce transaction costs for lenders.
- **Results-based financing (RBF) models:** Such as payment-for-performance and carbon credit schemes, offer innovative ways to attract climate and ecosystem service-linked funding.

These strategies are supported by the Agroforestry Investment Readiness Framework, which prepares agroforestry ventures for accessing blended finance, and the Climate-Smart Agriculture (CSA) Framework, which positions agroforestry as a key strategy for resilience and access to climate-related financial instruments.

Conclusion

Agroforestry offers a powerful solution to pressing environmental and socio-economic challenges, yet its widespread adoption remains constrained by systemic gaps in extension, policy, markets, and finance. Addressing these barriers requires a holistic and inclusive approach that empowers farmers through practical extension methodologies, supportive institutional frameworks, and innovative financing models. Strengthening community-based nurseries, market linkages, policy literacy, and financial access can transform agroforestry into a viable and sustainable livelihood strategy. With coordinated efforts from government, private sector, and civil society, agroforestry can move from the margins to the mainstream, fostering resilient landscapes, enhanced biodiversity, and improved rural livelihoods.

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Food Forest for Empowering Rural Livelihoods: Challenges & Way Forward

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Abstract

Food forests, also known as forest gardens, represent a regenerative and multifunctional agroforestry approach that integrates trees, shrubs, herbs, climbers, and groundcover species to mimic natural forest ecosystems while producing food and livelihood resources. This article explores the role of food forests in enhancing rural livelihoods by improving food and nutritional security, income diversification, ecological resilience, and community well-being. Drawing upon traditional knowledge systems, contemporary agroecological principles, and agroforestry science, the study highlights the ecological and socioeconomic benefits of food forests, including biodiversity conservation, soil and water management, carbon sequestration, and climate resilience. Despite their potential, the adoption of food forests faces challenges such as policy and institutional gaps, land tenure insecurity, limited technical knowledge, and weak market linkages. The article discusses design principles, species stratification, integration with existing farming systems, and sustainable management practices as key enablers for successful implementation. It further outlines a way forward through supportive policies, capacity building, research innovation, and value-chain development. Overall, food forests emerge as a viable, low-input, and climate-resilient strategy for sustainable rural development, providing a holistic pathway to enhancing livelihoods and restoring ecosystems.

Keywords: Food forest, Agroforestry, Rural livelihoods, Climate resilience, Biodiversity conservation, Sustainable agriculture

Introduction

A food forest, also known as a forest garden, represents a sustainable, multi-layered agroecosystem designed to mimic the structure and function of a natural forest while being primarily composed of edible and useful plant species. The fundamental idea is to integrate trees, shrubs, herbs, climbers, and groundcovers in such a way that they interact synergistically, enhancing productivity and ecological balance. Unlike monocropping systems, food forests embrace biodiversity, ecological succession, and natural nutrient cycling, thereby requiring minimal external inputs once established. Fruits are considered a primary source of nourishment and prosperity, essential for human sustenance and wellbeing.

Phalaiḥ puṣpaiḥ samiddhena homaḥ syād yajñakarmaṇi **(***Manusmṛti 3.76***)**
The shloka describes that fruit crops have long held ritual, cultural, and dietary importance in Indian civilization.

Phala-mūlāśanāḥ nityaṃ vane vasati jantavaḥ **(***Rāmāyaṇa, Araṇyakāṇḍa***)**
This shloka reflects the dependence of humans and wildlife on fruit-producing ecosystems, akin to food forests.

Phalāhāraḥ sadā śreyaḥ, deha-poṣaṇa-kārakaḥ |
Svasthaṃ kuryāj jagat sarvaṃ, poṣaṇena su-saṃyutaḥ ||

The diet based on fruits is always beneficial, as it nourishes the body. Through proper and balanced nourishment, it promotes health and well-being for all. Therefore, a fruit-based food forest will play a key role in empowering not only rural livelihoods but also in taking care of nutritional security.

Concept of Food Forests

A food forest typically consists of several layers—canopy (fruit/nut trees), understory trees, shrubs, herbs, ground covers, root crops, climbers, and fungi—which together create a self-sustaining system that provides food, fuel, fodder, fiber, and ecosystem services. This concept aligns closely with permaculture principles, emphasizing resilience, regeneration, and resource efficiency. In essence, a food forest is a human-designed analog of a natural forest ecosystem, aimed at producing food while restoring soil fertility, conserving water, and enhancing biodiversity. In modern discourse, food forests are increasingly recognized as nature-based solutions for addressing global challenges such as food insecurity, climate change, and land degradation, particularly in rural and resource-constrained settings.

Historical Background and Traditional Practices

The concept of food forests is not new; rather, it is deeply rooted in traditional and indigenous land-use systems across many parts of the world. Historical evidence suggests that forest-based food systems have existed for thousands of years in tropical regions of Asia, Africa, and South America. In India, traditional home gardens such as those in Kerala, Assam, and the Western Ghats are living examples of ancient food forests. These multi-tiered systems combine fruit trees, spices, vegetables, medicinal plants, and livestock in a compact and sustainable form of land management. Similarly, in Southeast Asia, the "Chagga home gardens" of Tanzania and "Kandyan gardens" of Sri Lanka illustrate long-standing traditions of integrated forest-agriculture systems. Historically, such systems played a critical role in ensuring food security, medicinal resources, and cultural identity for rural and tribal communities. They promoted nutrient recycling, maintained soil fertility, and reduced the need for chemical inputs long before modern sustainable agriculture terminology emerged. The decline of these traditional systems during the Green Revolution and subsequent agricultural industrialization has, however, led to biodiversity loss and ecological imbalance.

Reviving the ethnoecological knowledge underlying these practices offers valuable lessons for re-establishing sustainable and community-centered food systems. The fusion of traditional wisdom with contemporary agroecological science can thus pave the way for the modern food forest movement.

Relevance in Sustainable Rural Development

Food forests hold immense potential in empowering rural livelihoods through sustainable and regenerative land-use strategies. They offer multiple benefits that go beyond food production—enhancing income diversification, ecological resilience, and community well-being. For rural and marginalized populations, especially in regions affected by climate variability and resource scarcity, food forests provide a low-cost and high-impact model for self-sufficiency.

Economically, food forests can generate continuous income from a diverse range of produce—fruits, nuts, spices, honey, medicinal herbs, and timber—across different seasons. Environmentally, they contribute to carbon sequestration, soil conservation, water retention, and biodiversity restoration, aligning with global sustainability goals such as the UN Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land).

Socially, the participatory nature of food forests encourages community engagement, local governance, and gender inclusion, as women and smallholder farmers often play central roles in managing these systems. Moreover, they can serve as learning models for agroecological education and ecotourism, creating new livelihood pathways in rural areas.

In the broader context of sustainable rural development, food forests represent a transition from extractive agriculture to regenerative ecosystems, fostering harmony between people and nature. By integrating ecological design, traditional knowledge, and modern innovation, food forests emerge as a viable strategy for climate-resilient rural transformation and long-term livelihood security.

Ecological and Socioeconomic Importance of Food Forests

Food forests play a vital role in bridging ecological restoration and rural livelihood enhancement by combining biodiversity conservation, soil and water management, carbon sequestration, and livelihood diversification. As multifunctional agroecosystems, they provide ecosystem services that sustain both nature and people, positioning them as a cornerstone of sustainable rural development (Mbow et al., 2014; Kumar & Nair, 2004). The following sections discuss their ecological and socioeconomic importance in detail.

a. Biodiversity Conservation and Ecosystem Services:

Food forests represent one of the most effective agroecological strategies for conserving biodiversity within managed landscapes. They are designed to emulate the structure and ecological dynamics of natural forests, thereby supporting a wide range of flora and fauna, including pollinators, decomposers, and beneficial insects (Jose, 2009; Gliessman, 2015). The multilayered composition of food forests—ranging from canopy trees to groundcovers—creates diverse ecological niches that enhance species richness, genetic diversity, and ecosystem stability. The integration of indigenous and locally adapted species also promotes agrobiodiversity conservation, ensuring resilience against pests, diseases, and climatic fluctuations. By maintaining a mosaic of perennial plants, food forests function as refugia for native species and help prevent habitat fragmentation, a common outcome of monoculture farming. Furthermore, they support crucial ecosystem services such as pollination, pest regulation, nutrient cycling, and microclimate stabilization (Schroth et al., 2013).

b. Soil Health and Water Management

Food forests significantly enhance soil fertility and water retention capacity, contributing to the long-term sustainability of agricultural landscapes. The integration of trees and perennial vegetation promotes organic matter accumulation, root biomass, and biological activity in the soil, thereby improving soil structure, porosity, and nutrient cycling (Nair et al., 2009). Leaf litter and root turnover contribute to humus formation, which enhances the cation exchange capacity and water-holding ability of soils. The presence of nitrogen-fixing species (e.g., *Gliricidia sepium*, *Leucaena leucocephala*, *Albizia lebbeck*) within food forests naturally enriches the soil nutrient pool, reducing dependence on synthetic fertilizers. Mycorrhizal associations in these systems further enhance phosphorus availability and plant stress tolerance (Cardoso & Kuyper, 2006). In terms of water management, the multistrata canopy structure reduces evaporation and surface runoff, while deep-rooted trees facilitate groundwater recharge and prevent erosion. Studies have shown that agroforestry and food forest systems can improve soil infiltration rates and water-use efficiency, particularly in semi-arid and degraded landscapes (Verchot et al., 2007). These processes collectively improve the hydrological balance of the ecosystem and make food forests a natural solution for climate-adaptive water management**.**

c. Carbon Sequestration and Climate Resilience: Food forests are recognized as important carbon sinks, playing a dual role in mitigating and adapting to climate change. The perennial vegetation in food forests sequesters atmospheric CO_2 in above- and below-ground biomass and in soil organic matter, thus offsetting emissions from conventional agriculture (Montagnini & Nair, 2004; Mutuo et al., 2005). Research indicates that mature agroforestry systems can store 25–60 tonnes of carbon per hectare, depending on species composition, soil type, and climatic conditions (Nair et al., 2010). Beyond carbon storage, food forests enhance climate resilience by stabilizing microclimates, improving water regulation, and mitigating the impact of extreme weather events, such as droughts and floods. The integration of food forests into climate-smart agriculture strategies thus provides a pathway toward achieving net-zero emissions and ecosystem-based adaptation in rural landscapes (Lasco et al., 2014).

d. Livelihood Diversification and Food Security

From a socioeconomic perspective, food forests provide multiple livelihood opportunities while enhancing household food and nutritional security. Unlike monoculture systems that depend on a single harvest, food forests yield a wide array of products year-round, including fruits, nuts, vegetables, medicinal plants, honey, fodder, fiber, and timber (Kumar & Nair, 2004). This diversified production system ensures a steady flow of income and reduces vulnerability to market and climatic shocks. In rural contexts, especially in developing countries, food forests can play a transformative role in poverty alleviation and women's empowerment. Women often manage home gardens and small-scale food forests, giving them autonomy over resources and decision-making (Soemarwoto, 1987; Mohri et al., 2013). The surplus produce can be marketed locally, contributing to rural entrepreneurship, value addition, and agrobiodiversity-based enterprises. Moreover, the nutritional diversity provided by food forests addresses hidden hunger—the deficiency of micronutrients—by ensuring access to fresh, locally available, and chemical-free foods. By enhancing dietary diversity and resilience, food forests contribute directly to the UN SDGs, particularly SDG 1 (No Poverty) and SDG 2 (Zero Hunger).

Food Forests as a Tool for Rural Empowerment

Food forests represent an innovative and community-centered strategy for rural empowerment, integrating ecological restoration with socioeconomic development. By combining diverse perennial crops, traditional knowledge, and sustainable management practices, they enable rural communities to achieve income diversification, food and nutritional security, gender inclusion, and ecological stability. As multifunctional landscapes, food forests promote not only environmental sustainability but also social justice and local economic resilience (Kumar & Nair, 2004; Gliessman, 2015). 901–918.

The following are the ways through which food forests act as a tool for rural empowerment

- Livelihood Diversification and Income Generation
- Low-Input and Climate-Resilient Farming System
- Employment Generation and Skill Development
- Empowerment of Women and Marginalized Communities
- Improved Soil Health and Long-Term Productivity
- Reduced Production Risk and Economic Stability
- Community Participation and Social Cohesion
- Value Addition and Market Opportunities
- Alignment with Sustainable Development and Agroforestry Policies

Design and Establishment of Food Forests

The design and establishment of food forests require a systematic, ecological, and community-centered approach that aligns biodiversity conservation with livelihood objectives. Successful food forests are built upon sound ecological principles, appropriate species selection, and integrated management strategies that ensure productivity, resilience, and sustainability. The essential components and processes involved in developing effective food forest systems are mentioned below.

a. Principles of Permaculture and Agroforestry:

The foundation of a food forest lies in the principles of permaculture and agroforestry, which emphasize designing agricultural landscapes that function in harmony with natural ecosystems. Permaculture, derived from "permanent agriculture," advocates ecological design principles such as observe and interact, use and value diversity, integrate rather than segregate, and produce no waste (Mollison & Holmgren, 1979; Holmgren, 2002). These principles guide the creation of regenerative systems that mimic natural forests while meeting human needs sustainably. Agroforestry, on the other hand, integrates trees, crops, and sometimes livestock in spatial or temporal arrangements that enhance productivity, biodiversity, and ecosystem services (Nair, 1993; Jose, 2009). Food forests represent one of the most advanced forms of agroforestry, combining perennial polycultures with successional planning to ensure year-round yield and ecological balance. Designing a food forest involves understanding site-specific conditions—climate, soil type, hydrology, and sociocultural context—and applying ecological succession principles. Early stages may emphasize pioneer species that improve soil fertility and microclimate, followed by climax species that provide long-term stability. By combining permaculture ethics (earth care, people care, fair share) with agroforestry techniques, food forests emerge as resilient, low-input, and self-regulating systems that regenerate degraded landscapes and empower rural communities.

b. Species Selection and Stratification

Species selection and spatial arrangement form the ecological backbone of a food forest. The goal is to design a multi-layered system that optimizes sunlight capture, root distribution, and ecological interactions. Typically, a mature food forest comprises seven or more layers (Table 1):

Table 1. Layers of food forest, along with horticultural plants

S.N.	Layers	Description	Plants
1	Emergent Layer	Large Canopy Trees	Mango, Jackfruit, Mulberry, Manila Tamarind, Tamarind, Wood Apple, Coconut, Arecanut, Jamun, Water Apple, Mahua,
2	Canopy Layer	Medium Fruit and Nut Trees	Guava, Custard Apple, Aonla, Litchi, Sapota, Lasoda, Pomegranate

3	Understory Layer	Small Trees and Shrubs	Papaya, Banana, Drumstick, Curry Leaf, Karonda
4	Herbaceous Layer	Herbs, Vegetables, And Medicinal Plants	Turmeric, Ginger, Coriander, Fenugreek, Spinach, Tulsi
5	Groundcover Layer	Soil Protectors and Nitrogen Fixers	Sweet Potato, Cowpea, Peanut, Pumpkin,
6	Climbers/Vines	Creepers Producing Food	Grapevine, Passion Fruit, Black Pepper, Betelvine, Cucurbits
7	Root/Tuber Layer	Below-Ground Crops	Carrot, Radish, Beet Root, Yam, Taro/Colocasia, Elephant Foot Yam, Cassava, Radish,

Species selection should reflect local ecological conditions, cultural preferences, and market potential. Incorporating native and multipurpose species enhances biodiversity and resilience (Kumar & Nair, 2004). Additionally, functional diversity—such as nitrogen-fixing trees, pollinator attractors, pest-repellent herbs, and deep-rooted perennials—ensures ecological balance and reduces input needs (Garrity, 2004). The concept of stratification ensures vertical and temporal complementarity: upper layers capture sunlight while lower layers utilize filtered light, and root systems occupy different soil strata, reducing competition. Such design also supports year-round productivity and microclimate regulation, essential for food security and rural sustainability.

c. Integration with Existing Farming Systems

Integrating food forests into existing agricultural landscapes can enhance ecological stability and livelihood diversification without displacing conventional practices. This integration may take various forms-boundary plantations, alley cropping, homegardens, silvopastoral systems, and riparian buffers-depending on land availability, farmer preference, and regional ecology (Nair et al., 2010). For smallholders, food forests can be developed on marginal or degraded lands, providing an alternative income stream while restoring soil fertility and biodiversity (Mbow et al., 2014). On larger farms, they can be incorporated into fallow areas or farm boundaries to support pollinators, improve soil moisture, and reduce erosion. Integration with annual cropping systems allows transitional models where fast-growing perennials coexist with short-duration crops until canopy closure occurs. Moreover, food forests can strengthen community-based land management, encouraging collective ownership, cooperative marketing, and local governance of natural resources (Leakey, 2012). Integrating livestock—such as poultry, goats, or bees—further enhances nutrient cycling and income diversification. The compatibility of food forests with traditional homegardens and mixed-farming systems makes them ideal for promoting sustainable intensification in rural areas-producing more from less, without ecological degradation.

Management Practices and Sustainable Harvesting

Long-term success of food forests depends on adaptive management practices that maintain ecological balance while ensuring sustainable yields. Key management aspects include:

- Soil and nutrient management (mulching, composting, green manures, and nitrogen-fixing plants) (Cardoso & Kuyper, 2006).
- Water management (rainwater harvesting, contour bunding, and drip irrigation),
- Pest and weed control (Encouraging biological control agents such as predatory insects, birds, and companion planting instead of synthetic pesticides),
- Disease management
- Training and Pruning
- Sustainable harvesting
- Capacity building through farmer field schools, participatory training, and local cooperatives enhances local ownership and knowledge exchange (FAO, 2019).
- Digital tools and GIS mapping

Ultimately, sustainable management transforms food forests from static plantations into dynamic living systems, ensuring continuous regeneration, biodiversity conservation, and rural prosperity.

Challenges in Promoting Food Forests

The promotion of food forests faces several policy and institutional barriers that limit their large-scale adoption. In many regions, existing agricultural and forestry policies operate in isolation, with limited integration of agroforestry or food forest concepts into mainstream development programs. Lack of clear guidelines, weak inter-departmental coordination, and inadequate financial incentives discourage farmers from adopting multi-layered systems that do not fit neatly into conventional crop or forest classifications. Additionally, land tenure and ownership issues pose a major challenge, particularly in rural and tribal areas where land rights are unclear or insecure. Farmers with small, fragmented holdings or without formal land titles are often reluctant to invest in long-term tree-based systems due to fear of land alienation, restrictions on tree harvesting, or uncertainty regarding benefit sharing from forest-based produce.

Another critical challenge lies in knowledge gaps and technical limitations related to food forest design, species selection, and management practices. Many farmers and extension workers lack practical training in multi-strata planting, ecological interactions, and long-term maintenance of food forests, resulting in poor implementation or low productivity. The absence of location-specific research and standardized models further constrains adoption. Moreover, market access and value chain constraints reduce the economic attractiveness of food forests. Limited infrastructure for storage, processing, and transportation, along with weak market linkages for diverse and non-conventional products, often leads to post-harvest losses and low-price realization. Without organized value chains and assured markets, farmers find it difficult to fully capitalize on the economic potential of food forests, thereby slowing their wider promotion and acceptance.

Way Forward and Future Prospects

The way forward for food forests lies in scaling up proven models through supportive policies, integration with national agroforestry and climate-resilient agriculture programs, and financial incentives that encourage long-term tree-based systems. Strengthening capacity building, training, and community engagement is essential by empowering farmers, extension workers, women, and youth with practical knowledge on food forest design, management, and value addition through participatory approaches. At the same time, research and innovation should focus on developing location-specific food forest models, improved planting material, digital advisory tools, and evidence-based assessments of ecological and economic benefits. By linking food forests with efficient value chains, market access, and inclusive institutions, they can evolve into a powerful instrument for building a resilient, diversified, and inclusive rural economy that enhances livelihoods, nutritional security, and environmental sustainability under changing climatic conditions.

Conclusion

In conclusion, Food forests offer a holistic and sustainable pathway for empowering rural livelihoods by integrating ecological principles with diversified income, food, and nutritional security. The key insights highlight that multi-layered food forest systems enhance resilience to climate variability, reduce production risks, and create year-round livelihood opportunities, particularly for smallholders, women, and marginal communities, despite challenges related to policy gaps, land tenure insecurity, limited technical knowledge, and weak market linkages. To realize their full potential, policy and practice must prioritize supportive agroforestry frameworks, secure land and tree tenure, capacity building through extension and community-led training, and the development of inclusive value chains for diverse food forest products. With sustained research, innovation, and participatory governance, food forests can emerge as a transformative model for achieving sustainable, climate-resilient, and inclusive rural livelihoods while restoring ecosystems and strengthening local economies.

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ISBN
978-81-971641-6-3